

Exhibit 28

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

HONEYWELL INTERNATIONAL INC.
and HONEYWELL INTELLECTUAL
PROPERTIES INC.

Plaintiffs,

C.A. No. 99-309-GMS

v.

HAMILTON SUNDSTRAND CORP.,

Defendant.

**HONEYWELL'S RESPONSES TO
SUNDSTRAND'S FIRST SET OF INTERROGATORIES**

Plaintiffs Honeywell International Inc. and Honeywell Intellectual Properties Inc. (collectively, "Honeywell"), through their attorneys, hereby respond to defendant Hamilton Sundstrand Corporation's ("Sundstrand's") Interrogatories to plaintiffs as follows:

GENERAL OBJECTIONS

1. Honeywell objects to the Interrogatories, and the definitions of terms and instructions therein, on the grounds and to the extent that they purport to impose any obligations on Honeywell beyond those imposed by the Federal Rules of Civil Procedure and Local Rules of the United States District Court for the District of Delaware.

2. Honeywell objects to each and every paragraph of the Interrogatories that calls for information that is privileged or otherwise exempt from discovery in accordance with applicable law, including, without limitation, documents and information within the scope of the attorney-client privilege and work product doctrine. Similarly, Honeywell objects to the Interrogatories on the grounds and to the extent that they call for disclosure of information prepared in anticipation of litigation and/or trial preparation material without the showing

required by the Federal Rules of Civil Procedure. Honeywell hereby claims all privileges and protections applicable to the extent implicated by these Interrogatories, and excludes privileged and protected information from its responses to the Interrogatories. Any disclosure of such privileged or protected information would be inadvertent, and is not intended to waive such privileges and protections.

3. Honeywell objects to the Interrogatories on the grounds and to the extent that they seek information that, by reason of filing with public agencies or otherwise, is in the public domain or is readily accessible to Sundstrand, or is obtainable from some source other than Honeywell. Such Interrogatories are beyond the scope of permissible discovery and would impose an undue burden on Honeywell. Such information and documents are as available to Sundstrand as they are to Honeywell.

4. Honeywell objects to the Interrogatories on the grounds and to the extent that they are burdensome, oppressive, and overbroad, or to the extent that they seek information without reference to a time period, or to the extent that they seek information from a time period that is unreasonable and unnecessarily broad.

5. Honeywell objects to the terms "Plaintiff(s)," "you," "your" and "Honeywell" to the extent that such terms purport to include entities other than Honeywell International Inc., Honeywell Intellectual Properties Inc. or any predecessor corporations.

6. Honeywell objects to the Interrogatories to the extent they purport to require Honeywell to create documents that are not already in existence.

7. Honeywell objects to the Interrogatories on the grounds and to the extent that they seek information that is not reasonably calculated to lead to the discovery of admissible

evidence and to the extent that they are not relevant to the subject matter involved in the pending action.

8. Honeywell objects to the Interrogatories to the extent the Interrogatories are premature and reserves the right to supplement as appropriate.

SPECIFIC OBJECTIONS AND RESPONSES

In addition to the foregoing General Objections, which apply to each of these Interrogatories as if set forth fully with each specific objection and response below, Honeywell makes the following specific objections and responses, which Honeywell reserves the right to modify, supplement, or correct:

INTERROGATORY NO. 1: Identify and describe in detail the apparatus, structure or method utilized by or contained in the APS 3200 APU that Honeywell alleges the jury found to be the equivalent that infringed the IGV Limitations under the doctrine of equivalents in the verdict dated February 16, 2001.

RESPONSE TO INTERROGATORY NO. 1: Honeywell incorporates its general objections. Subject to and without waiving those objections, Honeywell responds as follows: As the special verdict form reflects, the jury found the specific surge control system of the APS 3200 APU, and the specific method of surge control practiced by that system, to infringe the IGV Limitations under the doctrine of equivalents.

INTERROGATORY NO. 2: Describe in detail the legal and factual basis for Honeywell's contention that the alleged equivalents identified in response to Interrogatory No. 1 were not foreseeable at the time of the Relevant Amendment Dates for the '893 Patent and the '194 Patent. (*Festo Corp. v. Shoketsu Kinzoku Kogyo Kabushiki Co.*, 535 U.S. 722, 740-41 (2002); *Honeywell International Inc. v. Hamilton Sundstrand Corp.*, 370 F.2d 1131, 1144 (Fed. Cir. 2004)).

RESPONSE TO INTERROGATORY NO. 2: Honeywell incorporates its general objections. Honeywell also objects to this interrogatory as premature to the extent it calls for the disclosure of expert testimony. Subject to and without waiving those objections, Honeywell responds as follows: Sundstrand's use of the patented technology in the APS 3200

was unforeseeable at the time of the Relevant Amendment Dates for several, independent reasons. Without limitation, these reasons include the following. First, as of 1983, it was not known in the art to measure static pressure in the diffuser as part of a delta P/P input to a surge control system of an APU. This is significant because the “inverted V/double solution” flow curve only arises in certain configurations in which the static pressure sensor is placed in the diffuser, as opposed to the compressor output, as was typical in the art at the time of the Relevant Amendment Dates. According to Sundstrand witnesses, it is the “inverted V/double solution” that led to Sundstrand’s unforeseeable use of inlet guide vane position in the surge control system of the APS 3200. Second, as Sundstrand has itself repeatedly asserted, the DELPQP parameter employed in the APS 3200 surge control system was a “unique” flow parameter that had never been used in an APU surge control system before its development in the late 1980s and early 1990s. As a result, Honeywell could not have foreseen at the time of the Relevant Amendment Dates the “unique” way that Sundstrand would choose to employ Honeywell’s patented technology. Third, Sundstrand’s particular use of the patented technology was not foreseeable at the time of the Relevant Amendment Dates because the APS 3200 uses ambient temperature in addition to IGV position to set the set point and determine whether and how to operate the surge control system. At the time of the Relevant Amendment Dates, it was contemplated that the patented technology would operate independently of ambient temperature. (See ‘893 Patent and ‘194 Patent, Col. 2, lines 63 - Col. 3, lines 2.) It therefore would have been unforeseeable at the time of the Relevant Amendment Dates that the inventions could be used in such a way as to incorporate ambient temperature. Fourth, Sundstrand’s particular use of the patented technology was not foreseeable at the time of the Relevant Amendment Dates because there was no example in the art at the Relevant Amendment Dates of a surge control system that

was configured and operated the same way as the surge control system of the APS 3200. Fifth, Sundstrand's particular use of the patented technology was not foreseeable at the time of the Relevant Amendment Dates because prior to the Patents-in-Suit, a load compressor could not operate continually close to a surge level. It was only with the new, patented ability to operate close to surge that the "inverted V/double solution" became relevant and useful, and therefore Sundstrand's use of inlet guide vane position in the surge control system of the APS 3200 to deal with the "inverted V/double solution" was necessarily unforeseeable at the time of the Relevant Amendment Dates.

Honeywell expressly reserves its right to amend and/or supplement this response.

INTERROGATORY NO. 3: Describe in detail the legal and factual basis for Honeywell's contention that the amendments made to the Patents-In-Suit on the Relevant Amendment Dates for the '893 Patent and the '194 Patent bore "no more than a tangential relationships" to the alleged equivalents identified in response to Interrogatory No. 1. (*Id.*)

RESPONSE TO INTERROGATORY NO. 3: Honeywell incorporates its general objections. Subject to and without waiving those objections, Honeywell responds as follows: The prosecution histories of the '893 Patent and '194 Patent establish that the amendments made to the Patents-in-Suit on the Relevant Amendment Dates bore no relationship, much less a tangential relationship, to the equivalent used by Sundstrand. There is no indication anywhere in the prosecution history that the would-be amendments at issue had anything to do with the IGV limitation. To the contrary, the Patent Examiner's rejections were based on the disclosure in the prior art of compressor control systems that included the use of proportional and integral controls to prevent surge. None of the prior art cited by Honeywell or by the Patent Examiner made any reference to the alleged equivalent, or to any use of IGV position in a surge control system. In addition, under the PTO procedure and rules during the relevant time period, the amendments at issue would have been considered amendments of form and not relevant to a

determination of claim scope or patentability. Because the amendments at issue were purely for form, and were not made in conjunction with a rejection related to patentability, they bore no relationship, much less a tangential relationship, to the equivalent used by Sundstrand.

INTERROGATORY NO. 4: Describe in detail the legal and factual basis for Honeywell's contention that "some other reasons" suggests that Honeywell could not reasonably be expected to have described the alleged equivalent identified in response to Interrogatory No. 1 when amending the patent claims on the Relevant Amendment Dates for the '893 Patent and the '194 Patent. (*Id.*)

RESPONSE TO INTERROGATORY NO. 4: Honeywell incorporates its general objections. Honeywell also objects to this interrogatory as premature to the extent it calls for the disclosure of expert testimony. Subject to and without waiving those objections, Honeywell responds as follows: There are a number of "other reasons" why Honeywell could not reasonably be expected to have described the equivalent used by Sundstrand at the time of the Relevant Amendment Dates. Without limitation, these include the following. First, a person of reasonable skill in the art at the time of the Relevant Amendment Dates would have believed that Honeywell was not disclaiming any patent scope by accepting the Patent Examiner's suggestion that it rewrite its dependent claims in independent form. A person of reasonable skill in the art at the time would not have believed that Honeywell was surrendering any patent coverage by agreeing to the Patent Examiner's offer. In fact, the corporate directive at Honeywell was precisely the opposite -- to draft claims as broadly as possible, knowing that the doctrine of equivalents was robust and would provide additional protection. Second, Honeywell was unable to capture the Sundstrand equivalent literally due to the limitations and inherent imprecision of language. Because of those limitations, it was impossible for Honeywell to describe literally every precise surge control system that would make use of the Honeywell inventions. This is especially true given the complexity of the Honeywell inventions as described in the prosecution histories and specifications of the Patents-in-Suit. Third, those

reasonably skilled in the art would have interpreted the asserted claims of the Patents-in-Suit to cover the Sundstrand equivalent because, *inter alia*, the equivalent used by Sundstrand on the APS 3200 is a less nuanced embodiment of the invention described in the Patents-In-Suit. As a result, those skilled in the art would have believed that Sundstrand's more simplistic embodiment was already encompassed by the sophisticated Patents-in-Suit, and there would have been no incentive to draft additional claims to provide redundant literal coverage.

INTERROGATORY NO. 5: Identify each individual having any information relating to Honeywell's responses to Interrogatory Nos. 1-4, including any individual on whom Honeywell may rely in attempting to meet its burden under *Festo Corp. v. Shoketsu Kinzoku Kogyo Kabushiki Co.*, 535 U.S. 722, 740-41 (2002) to rebut the presumption that Honeywell surrendered the alleged equivalents identified in response to Interrogatory No. 1, and describe in detail that individual's knowledge, information or proposed testimony.

RESPONSE TO INTERROGATORY NO. 5: Honeywell incorporates its general objections. Honeywell also objects to this interrogatory to the extent that it purports to require disclosure of expert testimony; Honeywell will disclose its expert testimony in accordance with the scheduling order in this matter. Honeywell also objects to this interrogatory as premature. Subject to and without waiving its objections, Honeywell preliminarily responds that the following people may have information relating to Honeywell's responses to Interrogatory Nos. 1-4: Milton Adams, Shauna Barkley, Jim Clark, Albert Ducrocq, Edward Edelman, Ed Goff, Alan Gruebel, Ken Henry, Kevin Jonestrask, Kurt Kenzler, J. Richard Konneker, Stephen R. LaCroix, Eric Moon, Richard F. Stokes, Peter Suttie, John Szillat and James D. Timm. Discovery has just begun, and Honeywell does not yet know in detail the extent of the knowledge, information or proposed testimony of each aforementioned individual.

INTERROGATORY NO. 6: Identify and describe any and all changes or developments in technology (including the date(s) such change or development occurred and became known in the art), occurring after the Relevant Amendment Dates for the '893 Patent and the '194 Patent, that would explain why the technology used in the alleged equivalent was unforeseeable at the time of the Relevant Amendment Dates.

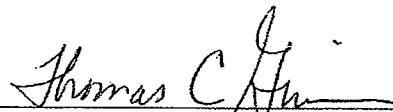
RESPONSE TO INTERROGATORY NO. 6: Honeywell incorporates its general objections. Honeywell also objects to this interrogatory as premature to the extent it calls for the disclosure of expert testimony. Honeywell further objects to this interrogatory as misleading and based on an erroneous premise to the extent it suggests that the foreseeability test could only be met based on a change or development in technology. Subject to and without waiving those objections, Honeywell responds as follows: As of 1983, it was not known in the art to measure static pressure in the diffuser as part of a delta P/P input to a surge control system of an APU. This is significant because the "inverted V/double solution" flow curve only arises, on certain occasions and in certain configurations, when the static pressure sensor is placed in the diffuser, as opposed to the compressor output, as was typical in the art at the time of the Relevant Amendment Dates. According to Sundstrand, it is the "inverted V/double solution" that led to Sundstrand's unforeseeable use of inlet guide vane position in the surge control system of the APS 3200. This change in technology took place in the late 1980s. Honeywell further incorporates by reference its Response to Interrogatory No. 2.

INTERROGATORY NO. 7: Identify all Honeywell APUs encompassed in the statement, in paragraph 10 of the Declaration of Jim Crocker Clark in Support of Honeywell's Responses to Sundstrand's Summary Judgment Motions, that "several of Honeywell's APUs – including the 331-350 – have the same 'inverted-V/double solution.'"

RESPONSE TO INTERROGATORY NO. 7: Honeywell incorporates its general objections. Subject to and without waiving its objections, Honeywell responds as follows: the Honeywell APUs that may exhibit the "inverted-V/double solution" flow curve are

the 331-350, 331-400, 331-500, 331-600, 131-9[A], 131-9[B], 131-9[D], 131-9[J] and 131-9[JC]. Honeywell further responds that all of these APUs were developed after 1985.

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October 3, 2005
485834

CERTIFICATE OF SERVICE

I hereby certify that on this 3rd day of October, 2005, copies of the foregoing were served upon counsel of record in the manner indicated:

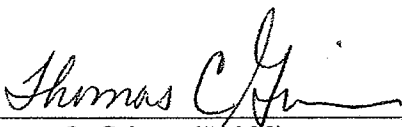
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Exhibit 29

SURGE
CONTROL
STUDY

FOR

**GTCIP331-350/
BOEING 767-400**

Ed Goff

Garrett Auxiliary Power Division

November, 1987

Allied-Signal Aerospace Company

MC 531-0



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SURGE CONTROL STUDY FOR GTP331-350 / BOEING 767-400

OUTLINE

- I BASIC REVIEW
- II CURRENT PROBLEM AREAS ON 331-200/250
- III ANALYSIS METHODS
 - 1. STEADY-STATE TOLERANCE ANALYSIS
 - 2. DYNAMIC ANALYSIS
- IV COMPARISON STUDY
 - 1. VALVE ACTUATION TYPES
 - A. PNEUMATIC POWER / ELECTRONIC SIGNAL (CURRENT 331-200 VALVE)
 - B. PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM
 - C. HYDRAULIC POWER / ELECTRONIC SIGNAL
 - D. AIRCRAFT TRANSIENT FLOW REQUIREMENTS
 - 2. FLOW MEASUREMENT TYPES
 - A. ΔP AND P_t PRESSURE SIGNALS
 - B. ALTERNATIVES
- V SUMMARY / PLANS

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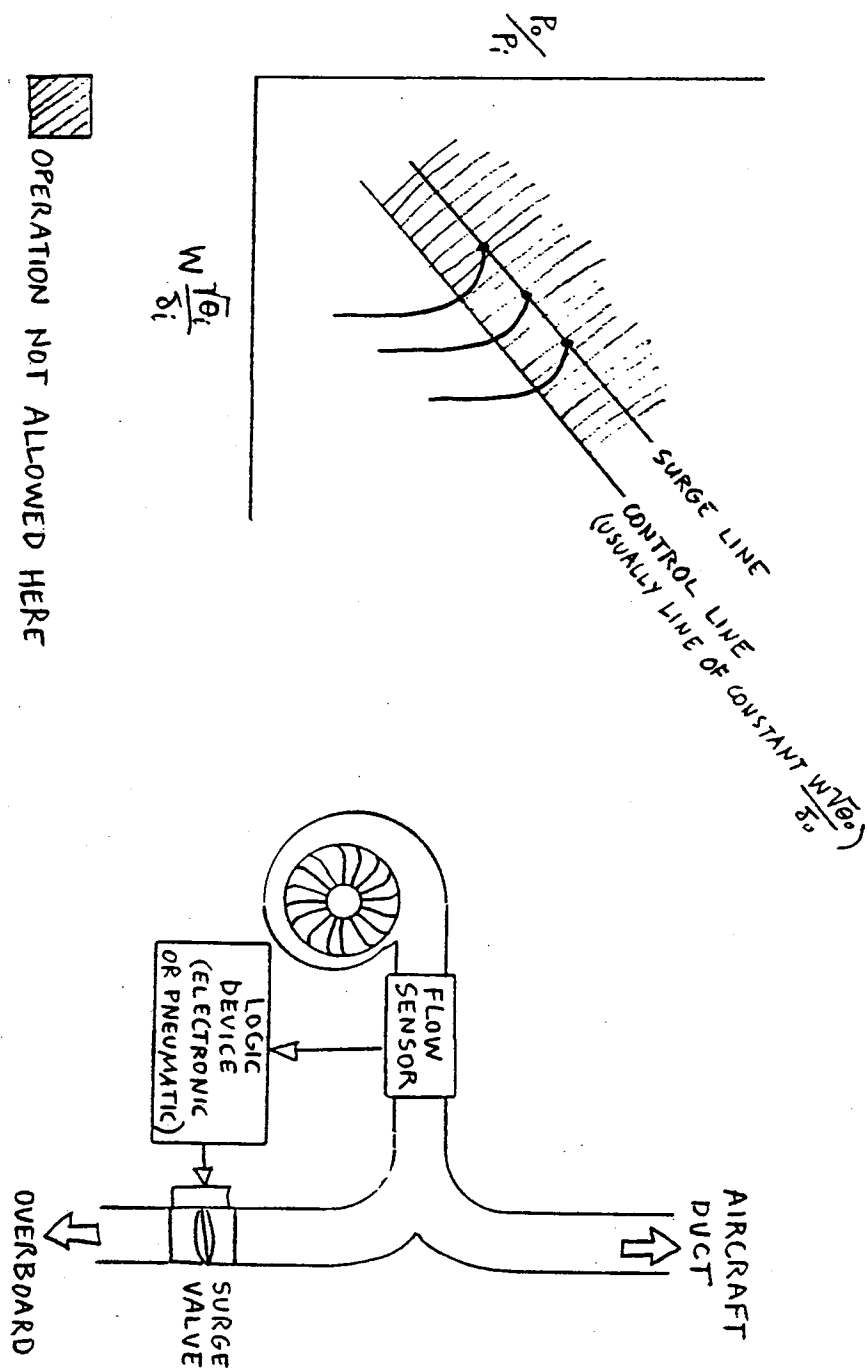
I
REVIEW OF SURGE CONTROL AND
THE GTCP331-200/250 SURGE CONTROL SYSTEM

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SURGE CONTROL SYSTEM PREVENTS LOW COMPRESSOR FLOW



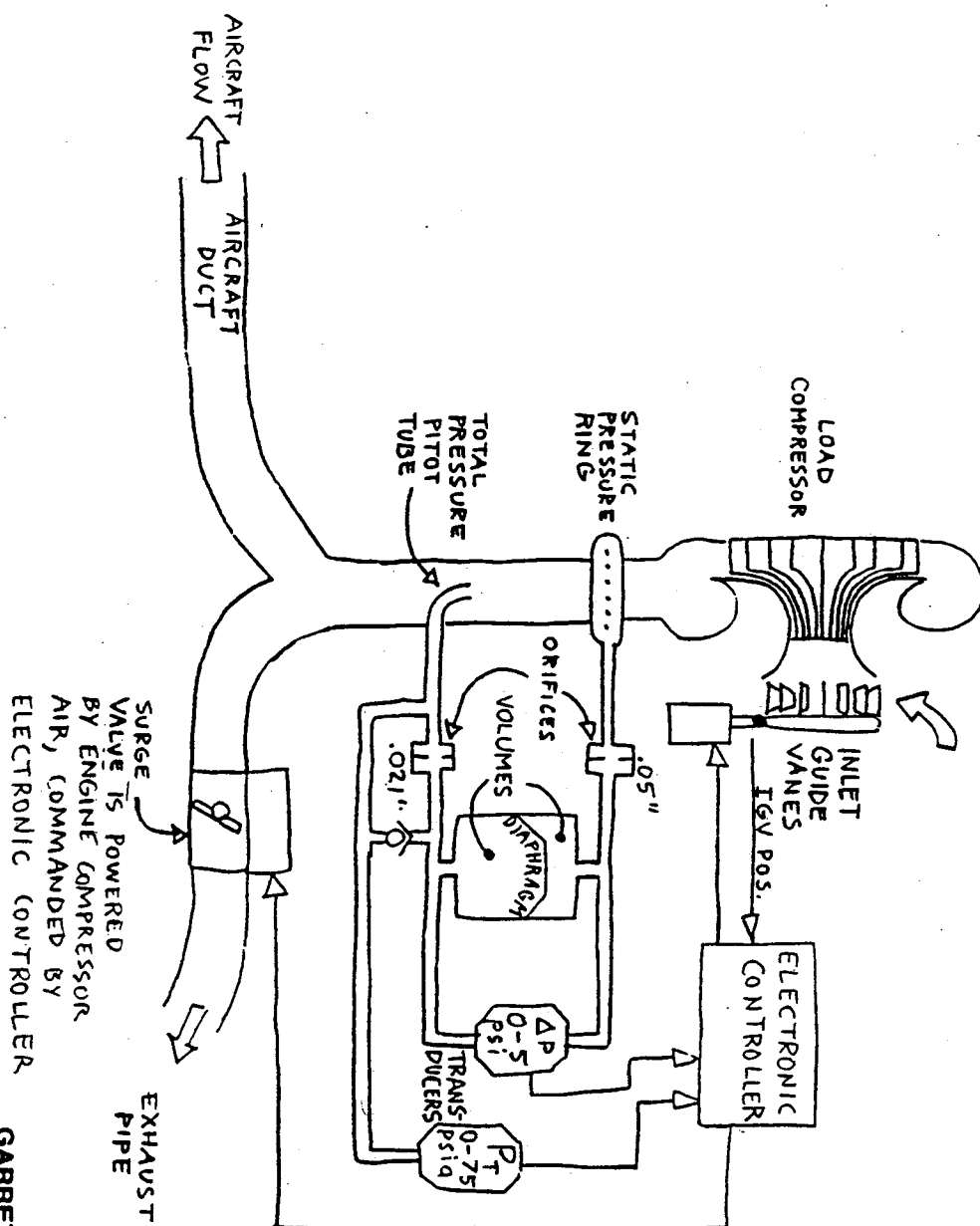
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GTCP 331-200/250 SYSTEM USES PRESSURE SENSING & PNEUMATIC VALVE



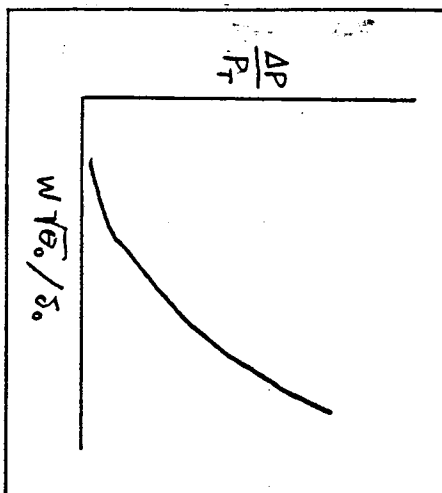
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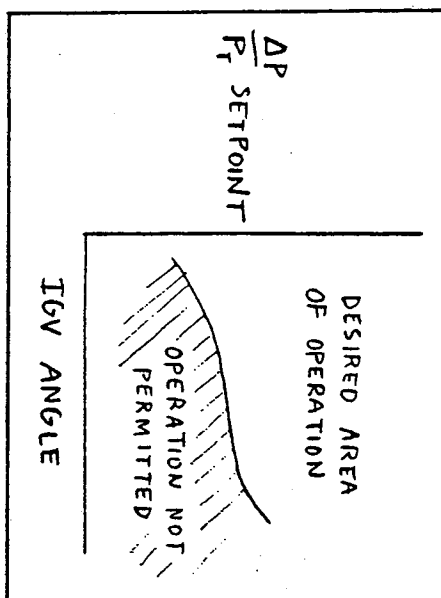


SYSTEM SENSES AND CONTROLS $\frac{\Delta P}{P_t}$, THEREBY REGULATING $W \sqrt{\frac{\theta_o}{\delta_o}}$ (GTC P331-200/250)



FLOW SENSOR
CHARACTERISTIC

- $\Delta P/P_t$ CORRESPONDS TO
DISCHARGE - CORRECTED FLOW



CONTROL SCHEDULE
IN ELECTRONIC CONTROLLER
MEMORY

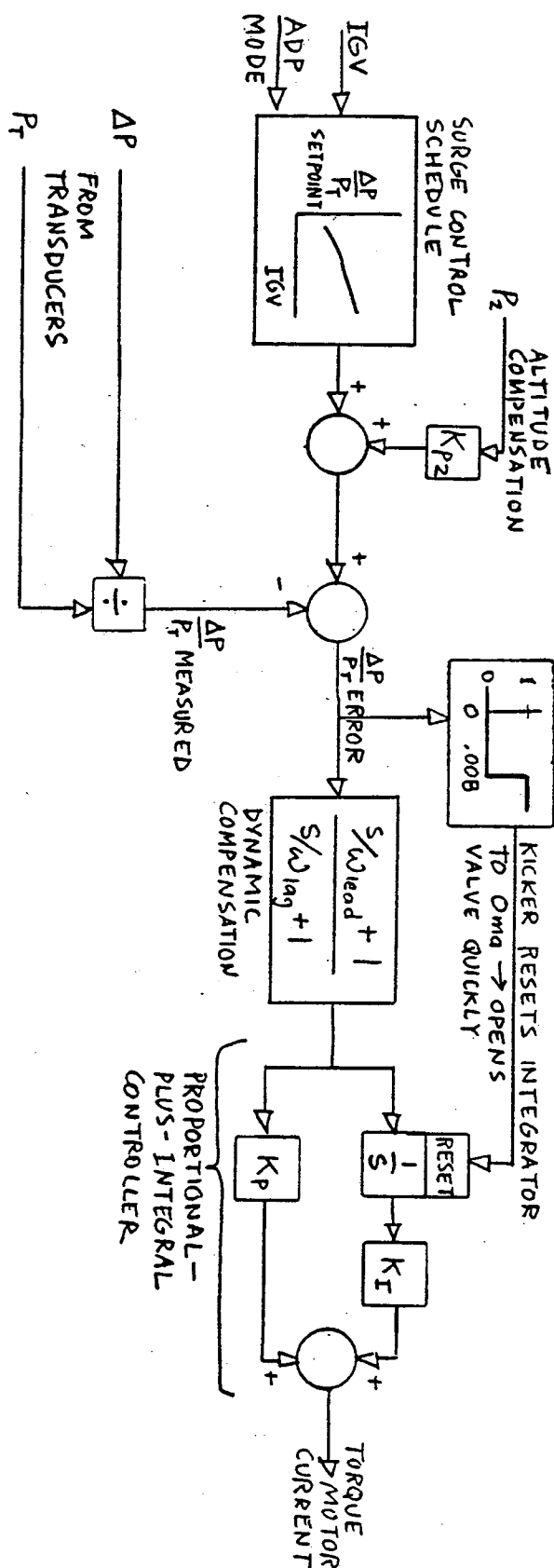
- SURGE VALVE IS COMMANDED
TO MAINTAIN $\Delta P/P_t$ AT OR
ABOVE THE SETPOINT

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GTCP331-200/250 HAS ELECTRONIC COMPUTER CONTROL



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II CURRENT GTCP331-200/250 PROBLEMS ARE
ADDRESSED IN GTCP331-350 DESIGN

- DYNAMICS
- TOLERANCE
- RELIABILITY

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331-200/250 DYNAMIC PROBLEMS ARE ADDRESSED

BASIC FREQUENCY RESPONSE OF SURGE VALVE IS RELATIVELY SLOW; SYSTEM RELIES ON "QUICK-DUMP" FEATURE FOR TRANSIENT RESPONSE. RESULTS IN NUISANCE "KICKS" DURING AIRCRAFT FLOW PERTURBATIONS AND POSSIBLE CYCLING. DUCT PRESSURE DROPS SIGNIFICANTLY FOLLOWING A KICK.

POSSIBLE SOLUTIONS

1. USE A FASTER SURGE VALVE WITHOUT A KICKER, RESULTING IN A MORE STABLE SYSTEM THAT WILL NOT KICK AND DROP THE DUCT PRESSURE DURING A FLOW TRANSIENT. SUCH A SYSTEM IS LINEAR FOR SMALL PERTURBATIONS AND CAN BE DESIGNED AND UNDERSTOOD USING CLASSICAL CONTROL STABILITY ANALYSIS.
2. USE THE KICKER ONLY IN AN OPEN-LOOP MODE, THAT IS, TRIGGERED BY ELECTRICAL SIGNALS FROM THE AIRCRAFT. AN AIRCRAFT SIGNAL WOULD HAVE TO ACCOMPANY EVERY RAPID FLOW DECREASE. SLOW FLOW CHANGES WOULD BE HANDLED BY CLOSED-LOOP CONTROL.

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331-200/250 TOLERANCE PROBLEMS ARE ADDRESSED

STEADY-STATE TOLERANCE OF FLOW SENSOR PLUS LOW ENGINE SURGE MARGIN RESULT IN SMALL TRANSIENT BAND ALLOWANCE. STATIC PRESSURE RING IS DIFFICULT TO MAKE, IS BUILT TO GEOMETRIC SPECS AND NOT FLOW TESTED, RESULTING IN SIGNIFICANT TOLERANCE SPREAD.

POSSIBLE SOLUTIONS

1. USE AN ADJUSTABLE FLOW SENSOR (PROBABLY ADJUSTABLE P_T PICKUP) WHICH IS CALIBRATED AND POSSIBLY MATCHED TO A COMPRESSOR, SIGNIFICANTLY REDUCING THE STEADY-STATE TOLERANCE BAND.
2. RUN THE LOAD COMPRESSOR AT HIGHER SURGE MARGIN
3. USE A DIFFERENT TYPE OF FLOW SENSOR, SUCH AS VORTEX-SHEDDING, WHICH IS PERHAPS MORE ACCURATE

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331-200/250 RELIABILITY PROBLEMS ARE ADDRESSED

ΔP TRANSDUCER RELIABILITY HAS BEEN VENDOR-SENSITIVE. ΔP TRANSDUCER CAN POSSIBLY BE OVER-RANGED BY MALFUNCTIONING ORIFICES, DFC (DIRECTIONAL FLOW CONTROL) OR VARIABLE-VOLUME CHAMBER. THE SYSTEM IS DIFFICULT TO TROUBLESHOOT; VARIOUS FAILURES CAN SHOW UP AS CONTROL LOOP CYCLING.

POSSIBLE SOLUTIONS

1. REMOVE THE OFFENDING TRANSDUCER VENDORS (THIS HAS ALREADY IMPROVED THE ΔP RELIABILITY)
2. REMOVE OR MODIFY THE ORIFICE-AND-VOLUME PRESSURE SIGNAL FILTERING TO PREVENT THE POSSIBILITY OF OVER-RANGING THE TRANSDUCERS.
3. USE A VENTURI STATIC PICKUP TO INCREASE THE ΔP SIGNAL LEVEL, ALLOWING USE OF A LARGER-RANGE, MORE RUGGED TRANSDUCER
4. USE A SURGE VALVE WITH DIRECT PNEUMATIC INPUT WHICH CAN RUN WITH REDUCED PERFORMANCE IF A TRANSDUCER FAILS.

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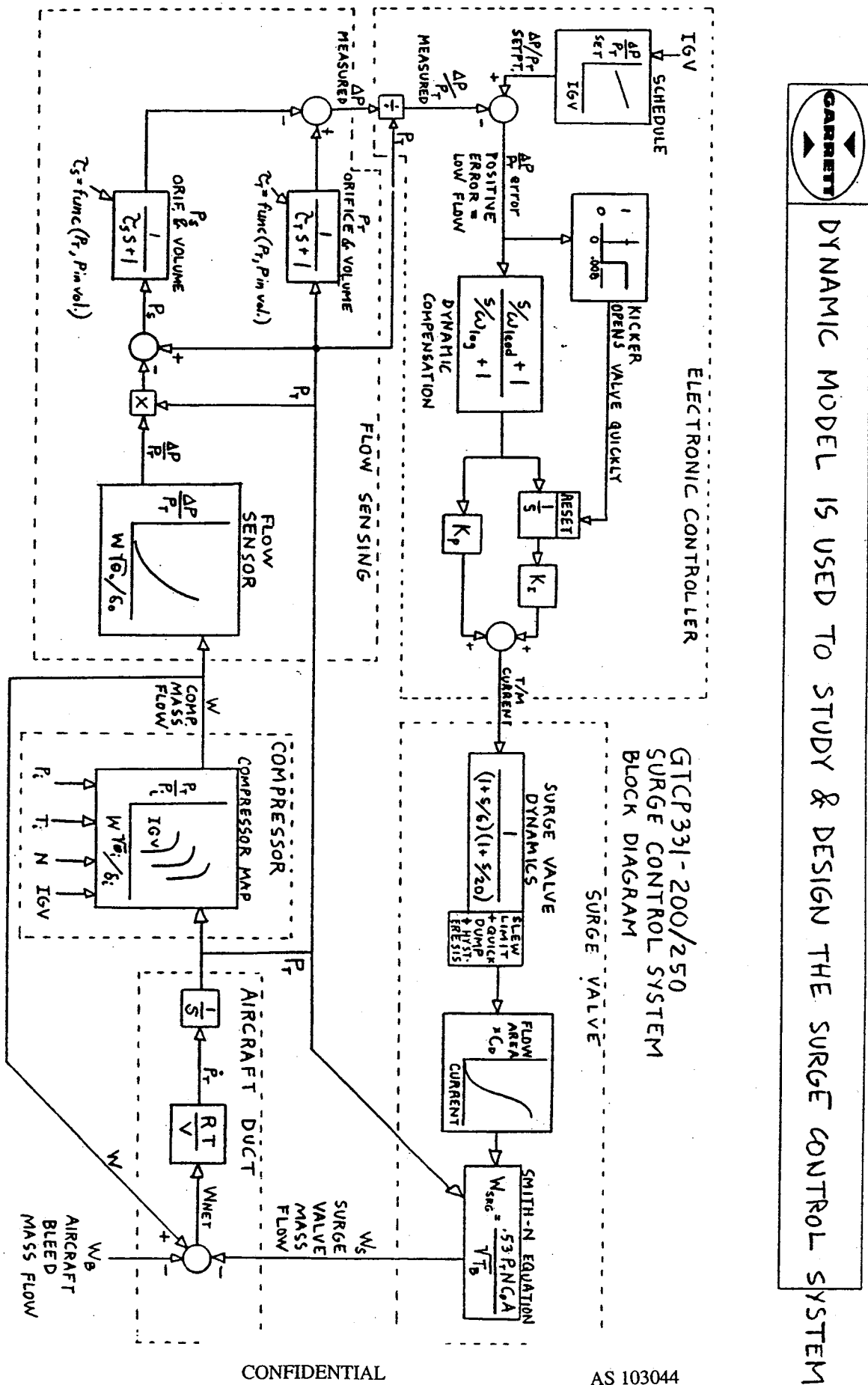
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III ANALYSIS METHODS

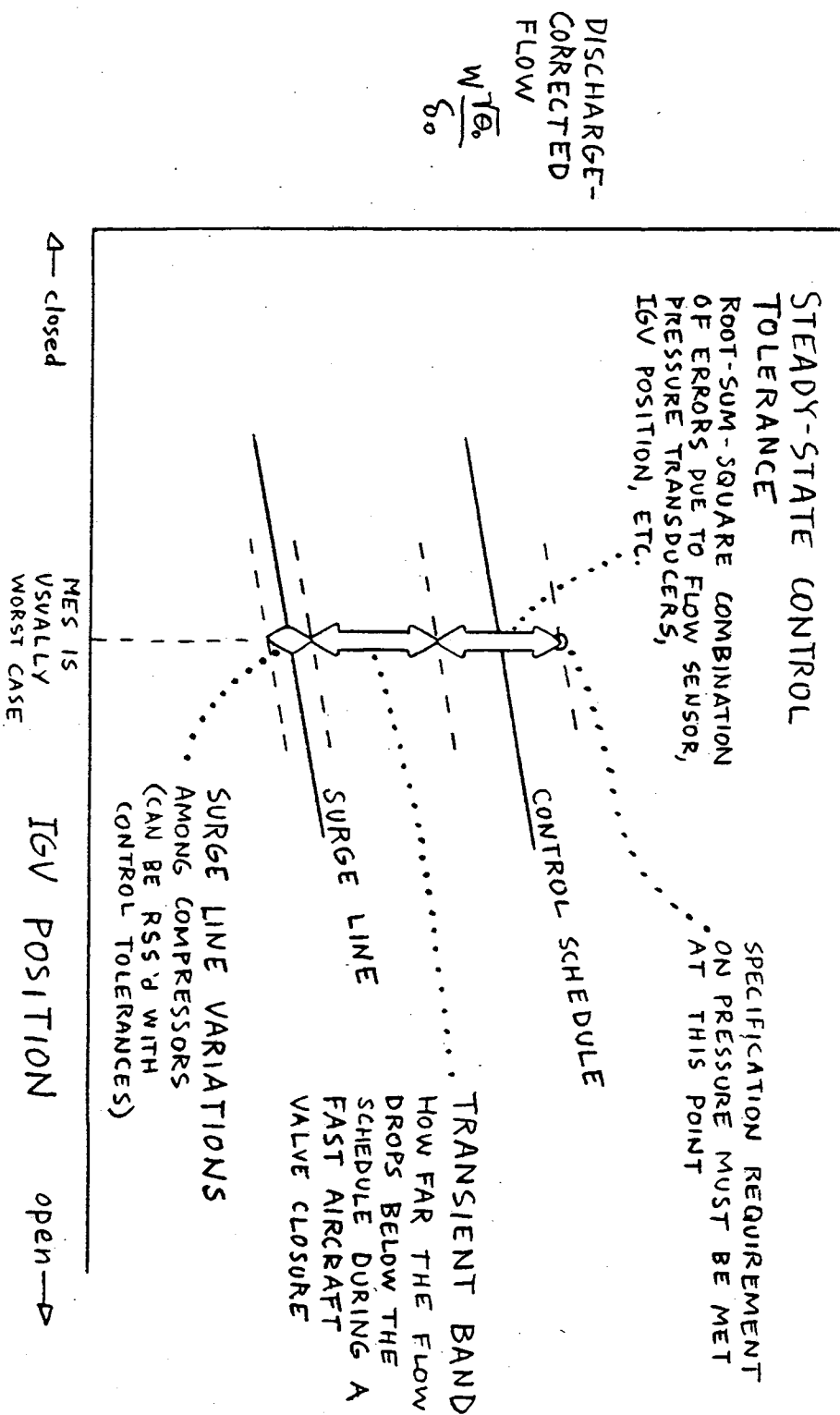
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PLACEMENT OF SETPOINT SCHEDULE DEPENDS ON SYSTEM ACCURACY & RESPONSE



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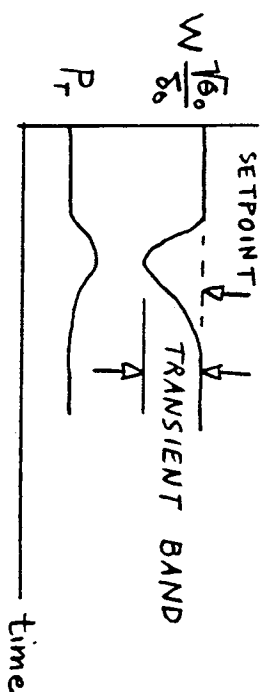
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TOLERANCE BANDS DEPEND ON COMPRESSOR, CONTROL SYSTEM, & AIRCRAFT

- STEADY-STATE BAND IS MOSTLY DUE TO FLOW SENSOR & TRANSDUCERS (ABOUT 50%), ALSO INCLUDES IGV POSITION ERROR (20%), ECU (10%), AND COMPRESSOR VARIATIONS (20%).
- TRANSIENT BAND IS EVALUATED BY COMPUTER SIMULATION OF THE SYSTEM DYNAMICS. (ACCURACY OF THE SIMULATION IS SUBSTANTIATED BY LAB TESTING. A SIMULATED AIRCRAFT VALVE CLOSING SHOWS HOW FAR THE FLOW DROPS BELOW THE SETPOINT.



- THE REQUIRED TRANSIENT BAND DEPENDS ON THE SHAPE OF THE COMPRESSOR MAP (ESPECIALLY THE PRESSURE RATIO MARGIN), THE CONTROL LOGIC, THE SURGE VALVE RESPONSE, AND THE AIRCRAFT DUCT VOLUME.

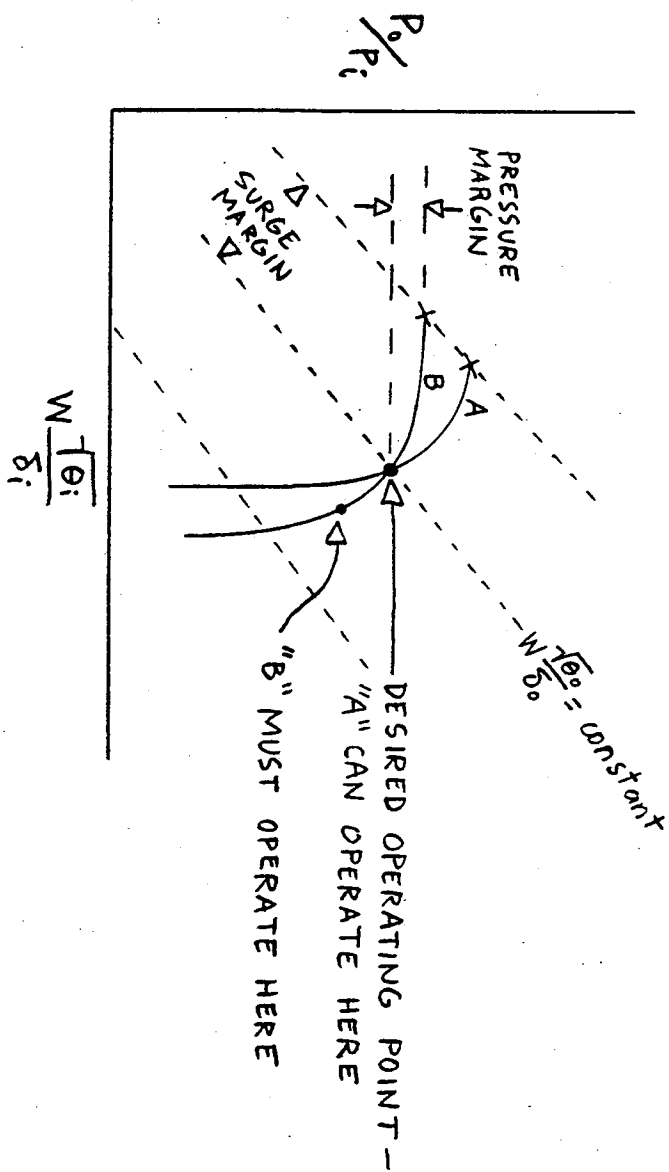
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PRESSURE RATIO MARGIN AFFECTS TRANSIENT BAND



COMPRESSORS A AND B HAVE THE SAME SURGE MARGIN (IN TERMS OF DISCHARGE-CORRECTED FLOW), BUT B REQUIRES A MUCH LARGER TRANSIENT BAND (IN TERMS OF DISCHARGE-CORRECTED FLOW) AND MUST HAVE A SURGE CONTROL SETPOINT AT A LOWER PRESSURE BECAUSE OF ITS LOW PRESSURE-RATIO MARGIN.

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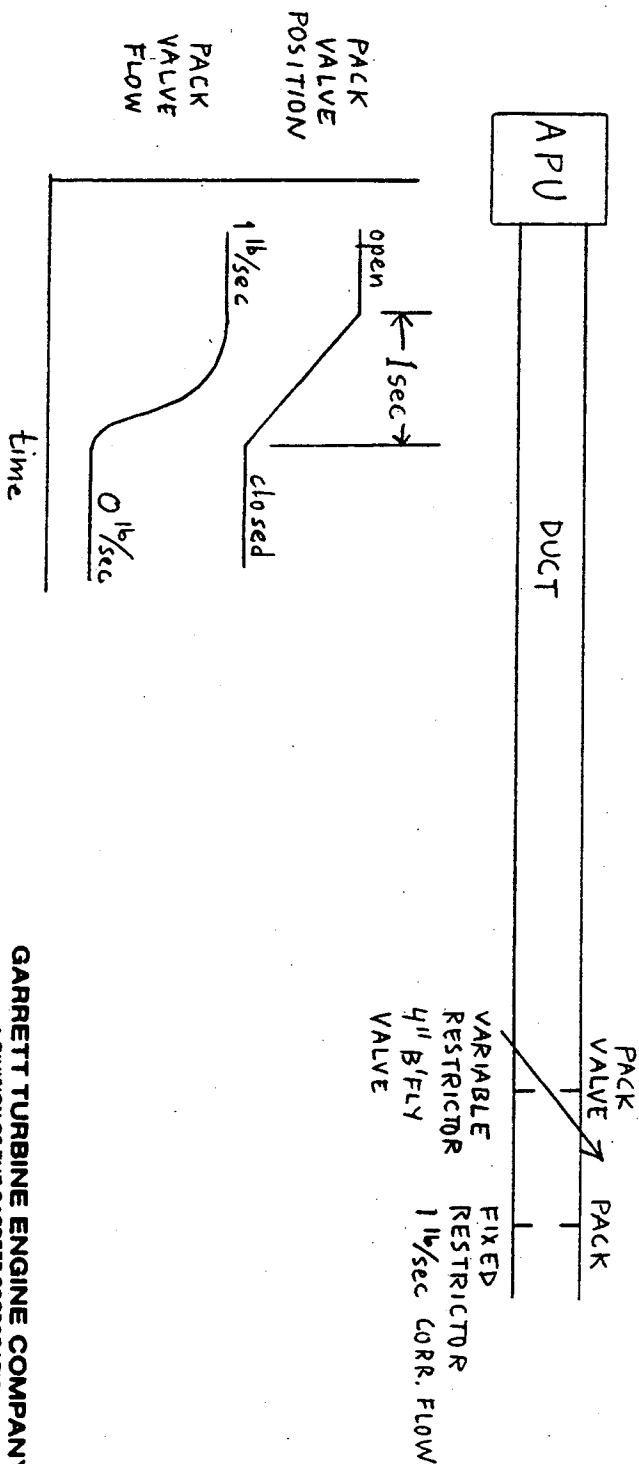
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PACK VALVE CLOSURE IS WORST-CASE TRANSIENT

- FOR THIS STUDY, A SINGLE PACK VALVE CLOSURE IS CONSIDERED THE WORST-CASE AIRCRAFT FLOW TRANSIENT. (1 SEC. CLOSING TIME)
- AN AIR TURBINE STARTER VALVE CLOSURE OR A DOUBLE PACK VALVE CLOSURE WOULD BE ACCOMPANIED BY A MODE-CHANGE ELECTRONIC SIGNAL FROM THE AIRCRAFT.

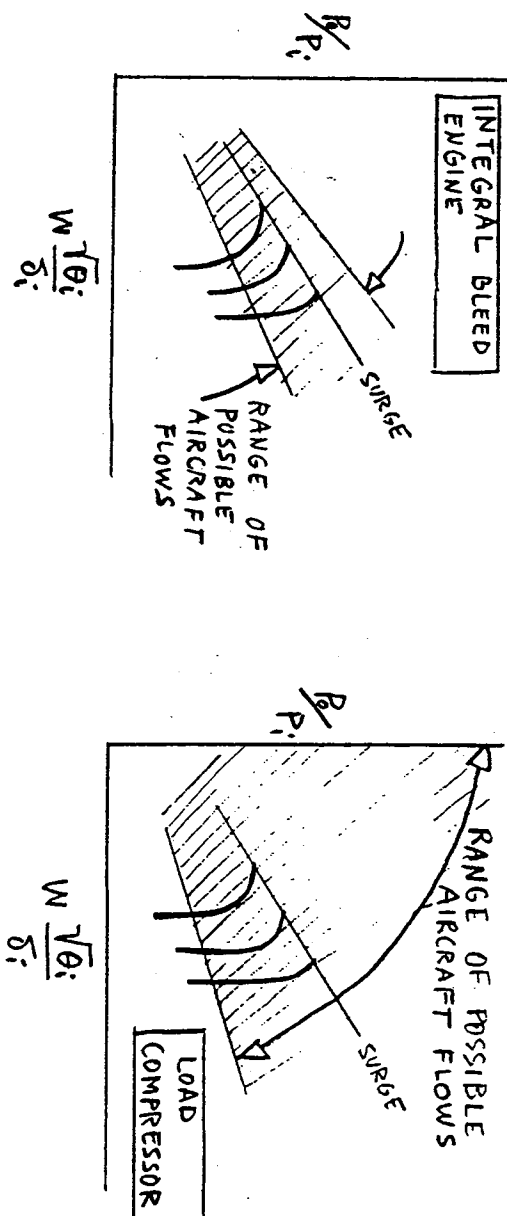


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GARRETT
LOAD COMPRESSORS HAVE TOUGH SURGE CONTROL REQUIREMENTS



- A FLOW SENSOR ACCURACY OF $\pm 5\%$ OF THE FLOW SENSOR'S RANGE TRANSLATES INTO A MUCH LARGER SURGE MARGIN ON A LOAD COMPRESSOR THAN ON AN INTEGRAL BLEED ENGINE
- A TYPICAL TRANSIENT FLOW UNDERSHOOT CAUSED BY AN AIRCRAFT VALVE CLOSURE TRANSLATES INTO MORE SURGE MARGIN ON A LOAD COMPRESSOR THAN ON AN INTEGRAL BLEED ENGINE.

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IV COMPARISON STUDY

- COMPARISON OF VALVE ACTUATOR TYPES
- COMPARISON OF FLOW SENSOR TYPES

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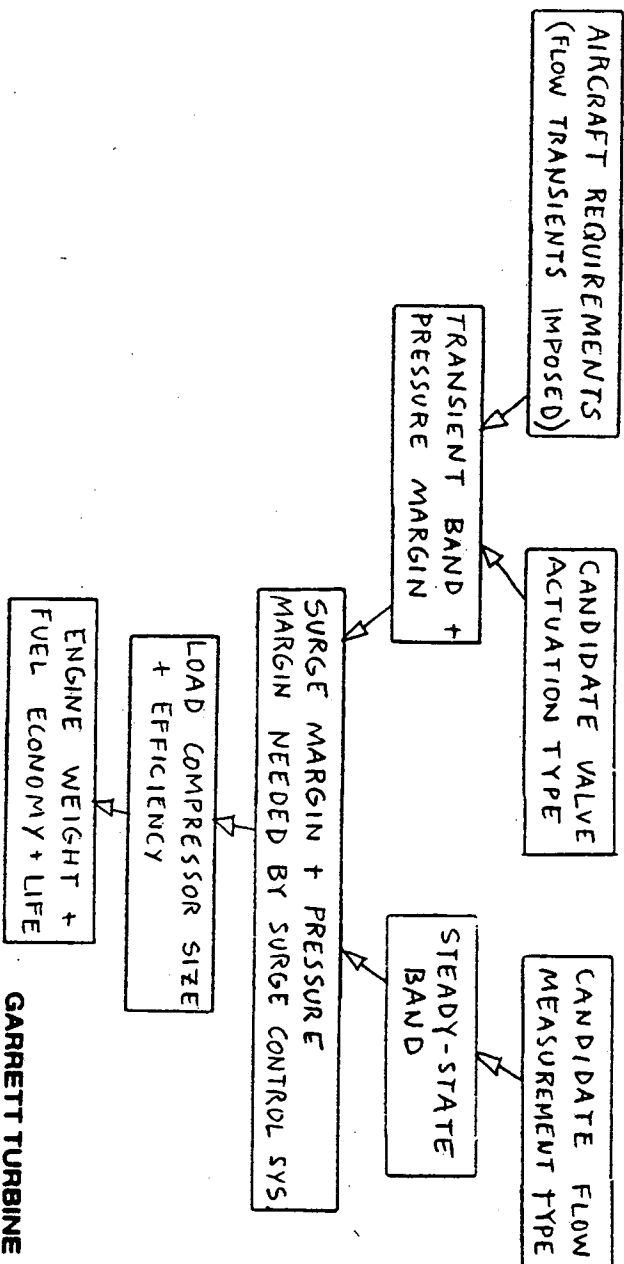


COMPARISON STUDY RE-CONSIDERS ALL ASPECTS OF THE SYSTEM

• IN GENERAL, THE VALVE ACTUATION TYPE AND THE AIRCRAFT REQUIREMENTS DETERMINE THE TRANSIENT BAND, AND THE FLOW MEASUREMENT TYPE DETERMINES THE STEADY-STATE TOLERANCE.

• THE COMBINATION OF TRANSIENT AND STEADY-STATE BANDS DETERMINES THE REQUIRED COMPRESSOR SURGE MARGIN.

• THE LOAD COMPRESSOR SIZE AND EFFICIENCY DEPENDS ON THE SURGE MARGIN.



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FOUR VALVE-ACTUATION TYPES HAVE BEEN STUDIED

VALVE ACTUATION TYPES ARE CLASSIFIED BY POWER SOURCE, PRIMARY SIGNAL TYPE, AND (POSSIBLY) TRIM SIGNAL TYPE

- A PNEUMATIC POWER / ELECTRONIC SIGNAL / QUICK-DUMP (GTCP331-200/250) TORQUE MOTOR INPUT - SLOW RESPONSE (CORNER FREQUENCY ≈ 1 Hz or 6 rad/sec)
- B PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM (B-1 or MD-11) DIRECT ΔP FROM FLOW SENSOR - FASTER RESPONSE (≈ 4 Hz or 25 rad/sec)
- C HYDRAULIC POWER / ELECTRONIC SIGNAL
ELECTRO-HYDRAULIC ACTUATOR ~~≡~~ ~~FAST~~ (≈ 16 Hz or 100 rad/sec)
- D HYDRAULIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM
DIRECT ΔP FROM FLOW SENSOR - SAME PERFORMANCE AS C.

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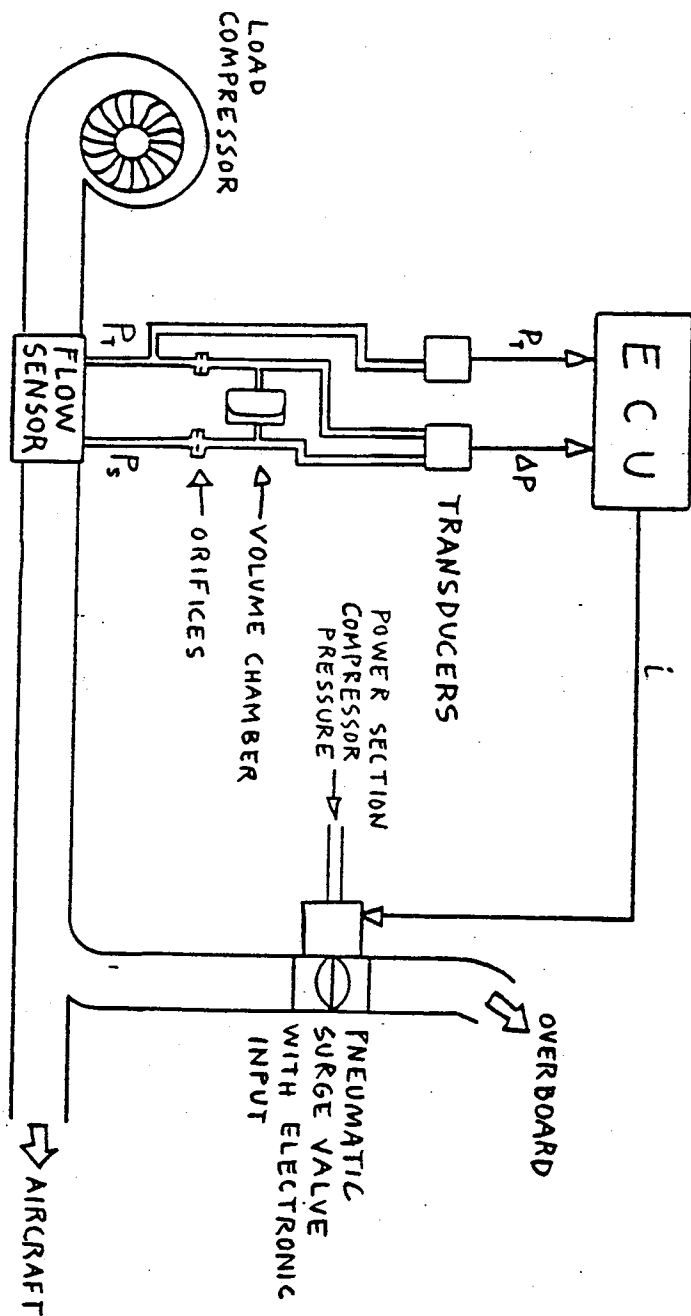
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VALVE ACTIVATION 1

A. PNEUMATIC POWER

ELECTRONIC SIGNAL (34-100/250)

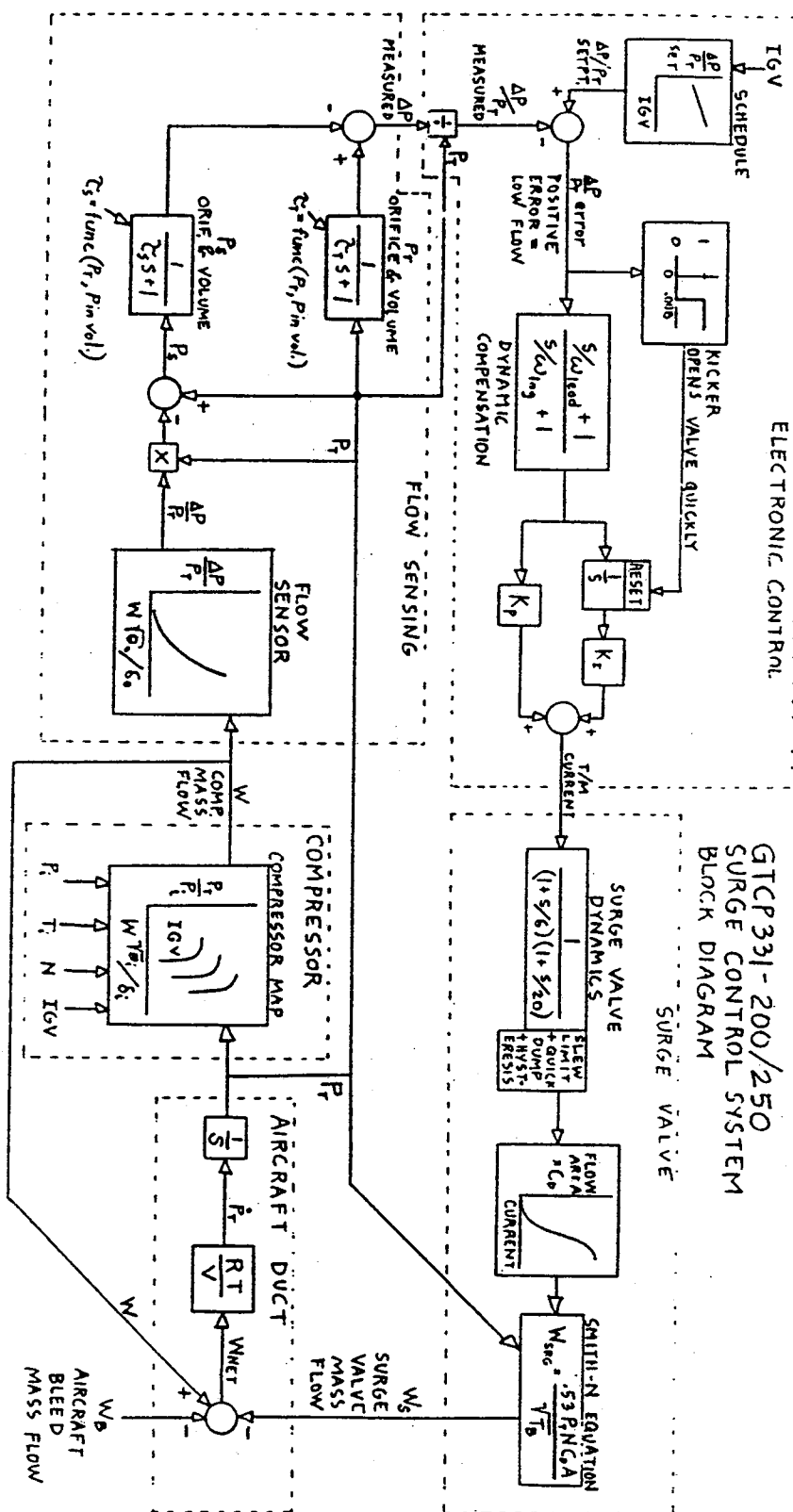


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GARRETT
VALVE ACTUATION TYPES
A. PNEUMATIC POWER / ELECTRONIC SIGNAL (331-200/250)



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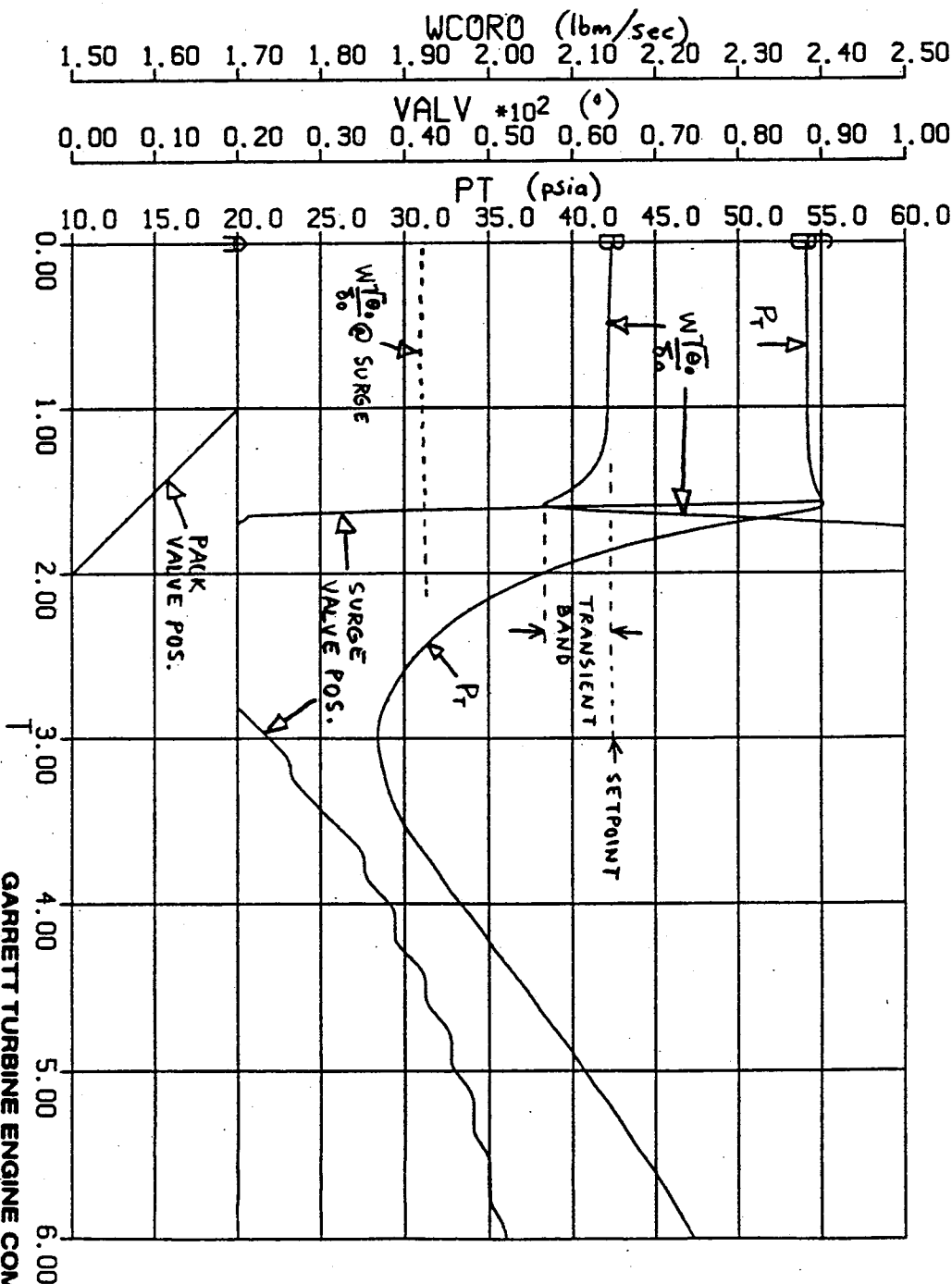
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VALVE ACTUATION TYPES

A. PNEUMATIC POWER / ELECTRONIC SIGNAL / QUICK-DUMP (331-200/250)

1 SEC PACK VALVE CLOSURE



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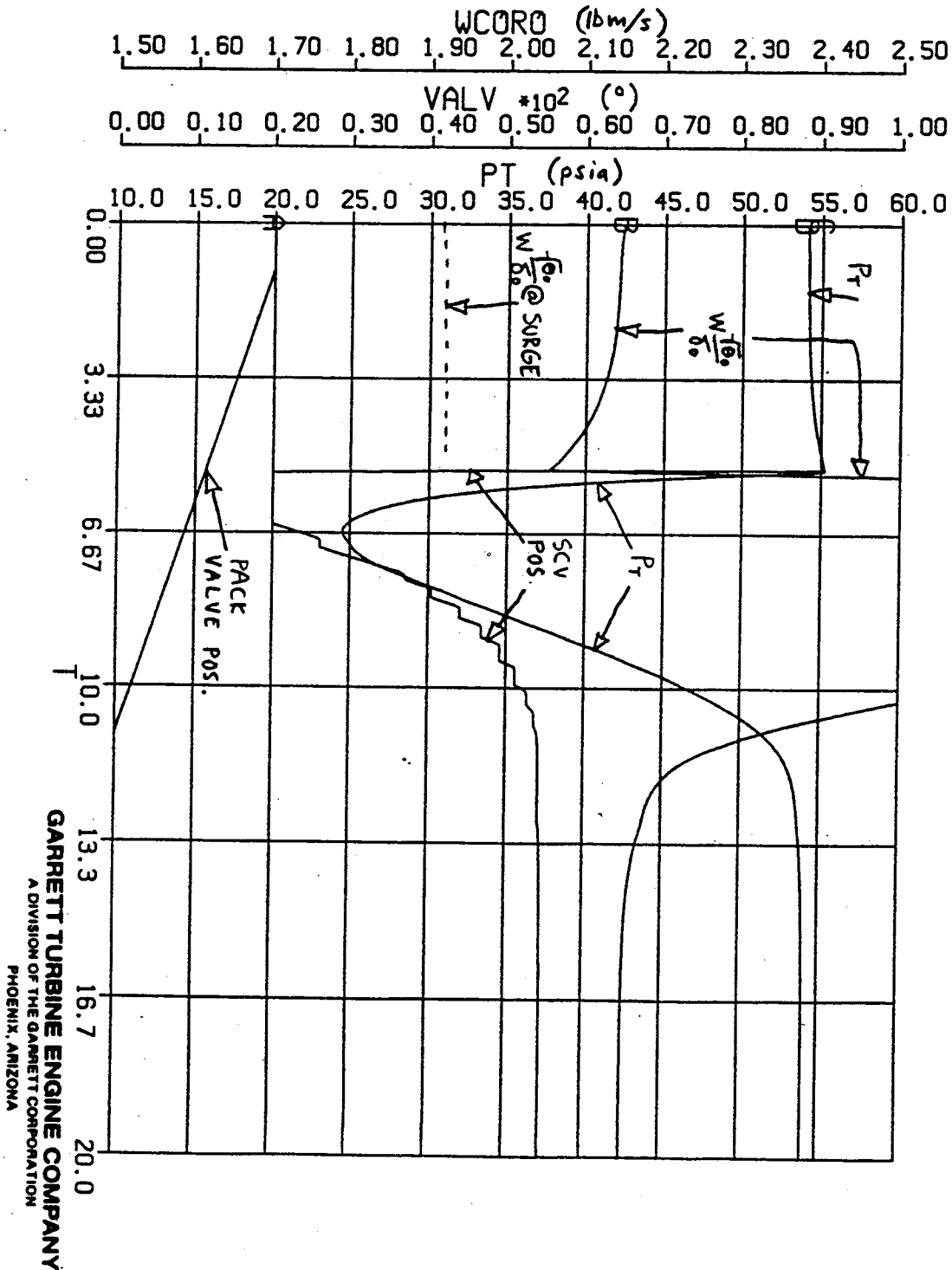
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VALVE ACTUATION TYPES

A. PNEUMATIC POWER / ELECTRONIC SIGNAL / KICKER (331-200/250)

10 SEC PACK VALVE CLOSURE



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A. PNEUMATIC POWER / ELECTRONIC SIGNAL (331-200/250)

- VALVE IS A PROVEN DESIGN
- RESPONSE OF VALVE ANGLE TO INPUT CURRENT IS MUCH TOO SLOW TO HANDLE REASONABLE TRANSIENTS. A "QUICK DUMP" MECHANISM MUST BE USED.
- THE QUICK DUMP AND ELECTRONIC KICKER COMBINED WITH THE ORIFICE- AND-VOLUME LEAD EFFECT PROVIDE EXCELLENT SURGE PROTECTION WITH A VERY SMALL TRANSIENT BAND, BUT CAUSE STABILITY PROBLEMS THAT ARE DIFFICULT TO DEAL WITH.

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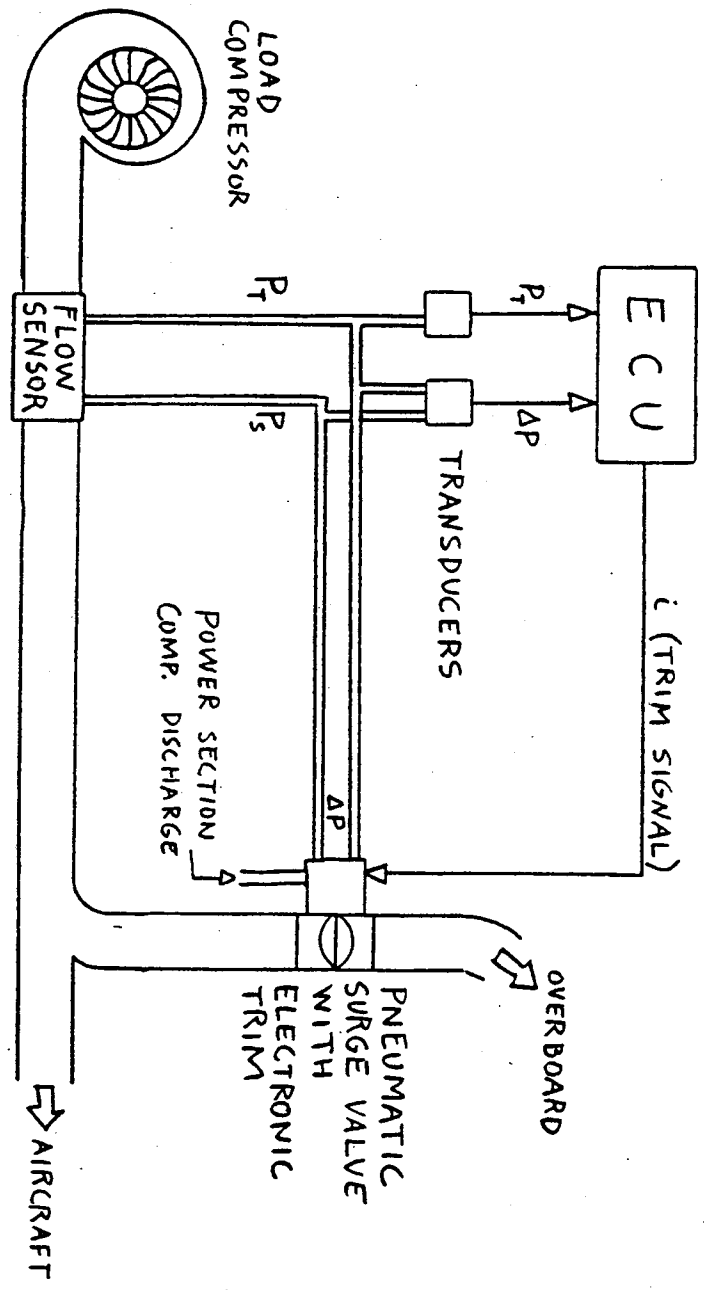
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VALVE ACTUATION TYPES
B. PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM (B-1 VALVE)

SCHEMATIC



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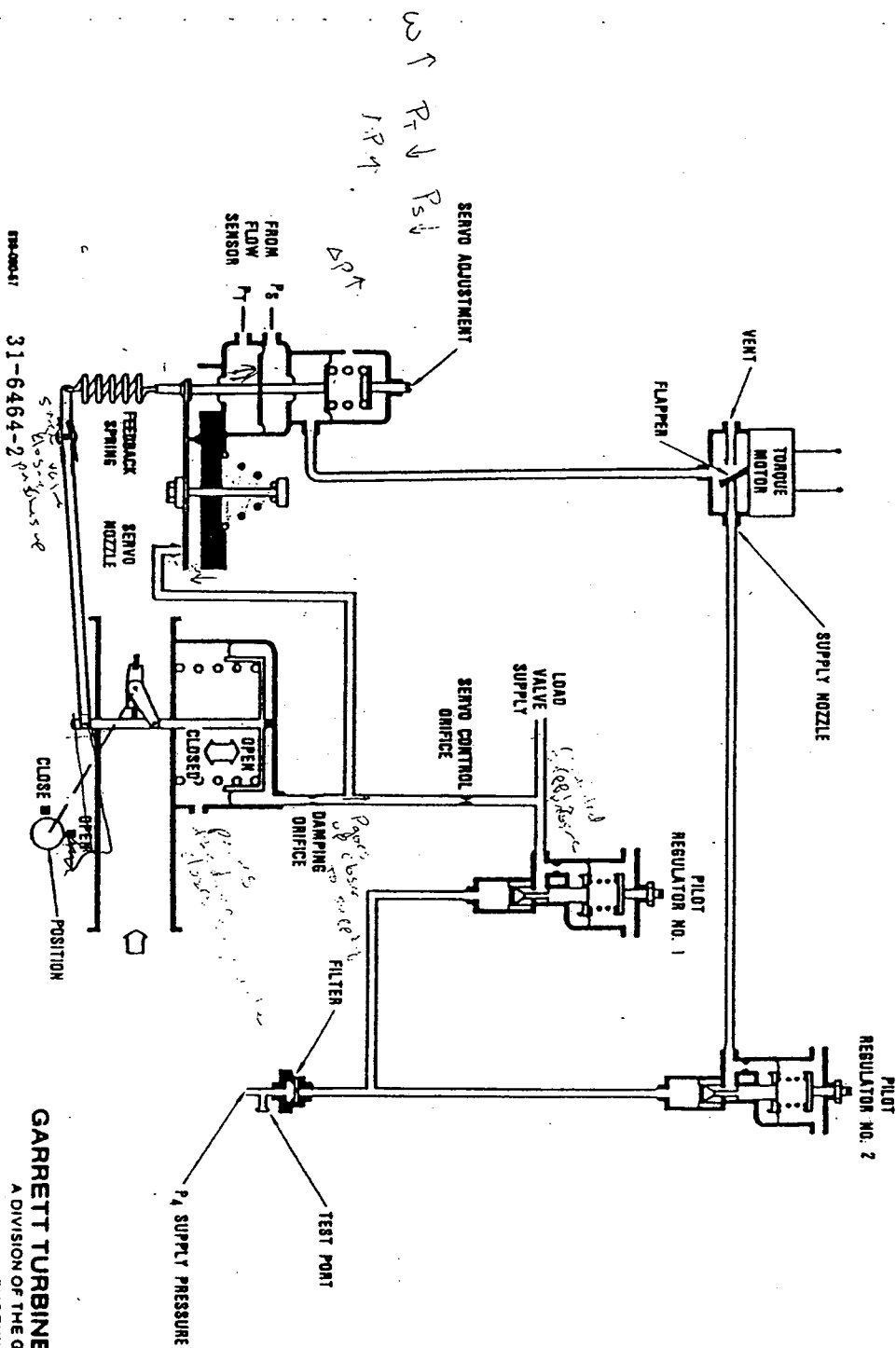
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VALVE ACTUATION LINES

B. PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRAIN

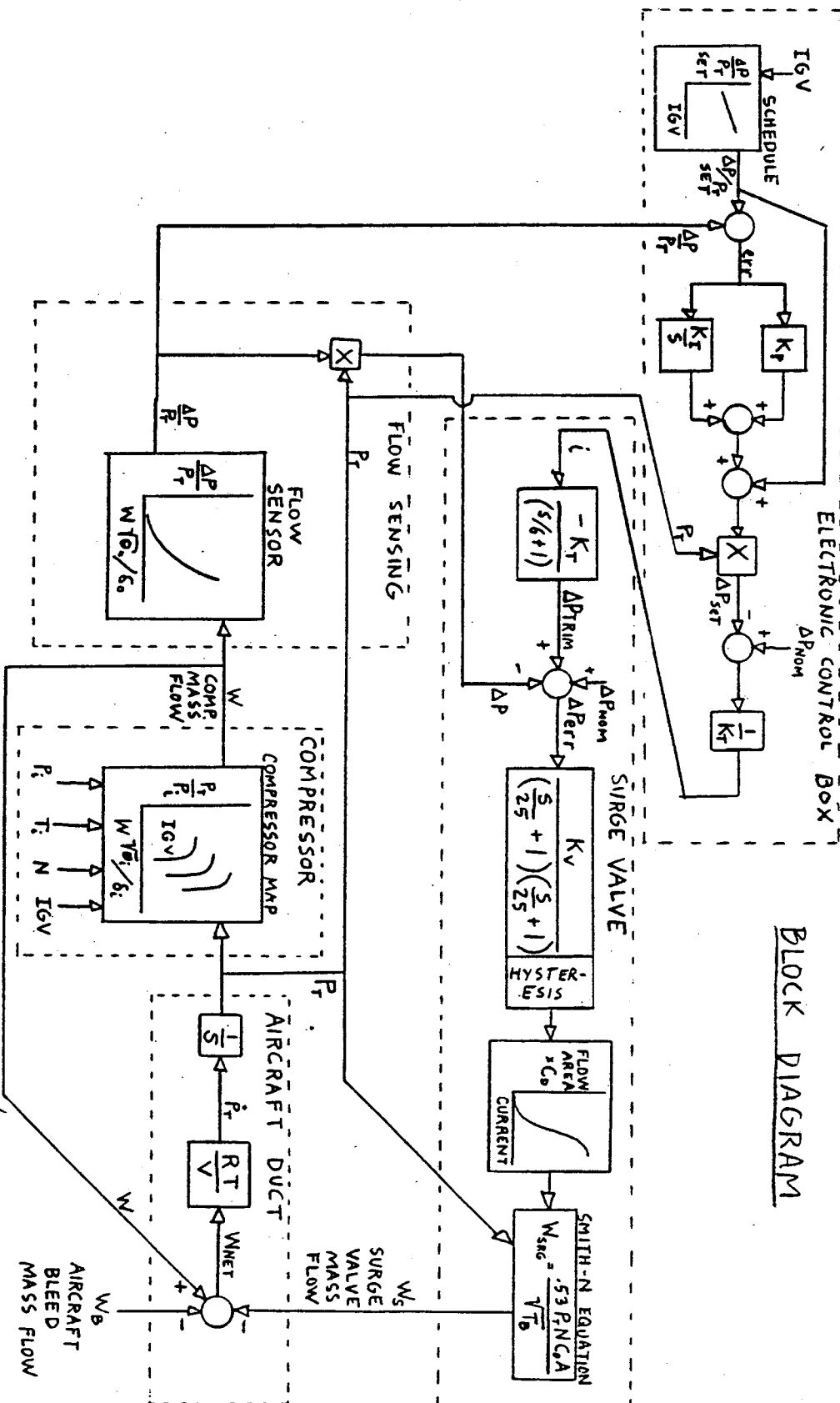
B-1 SURGE VALVE SCHEMATIC



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VALVE ACTUATION TYPES
B. PNEUMATIC POWER/PNEUMATIC SIGNAL/ELECTRONIC TRIM



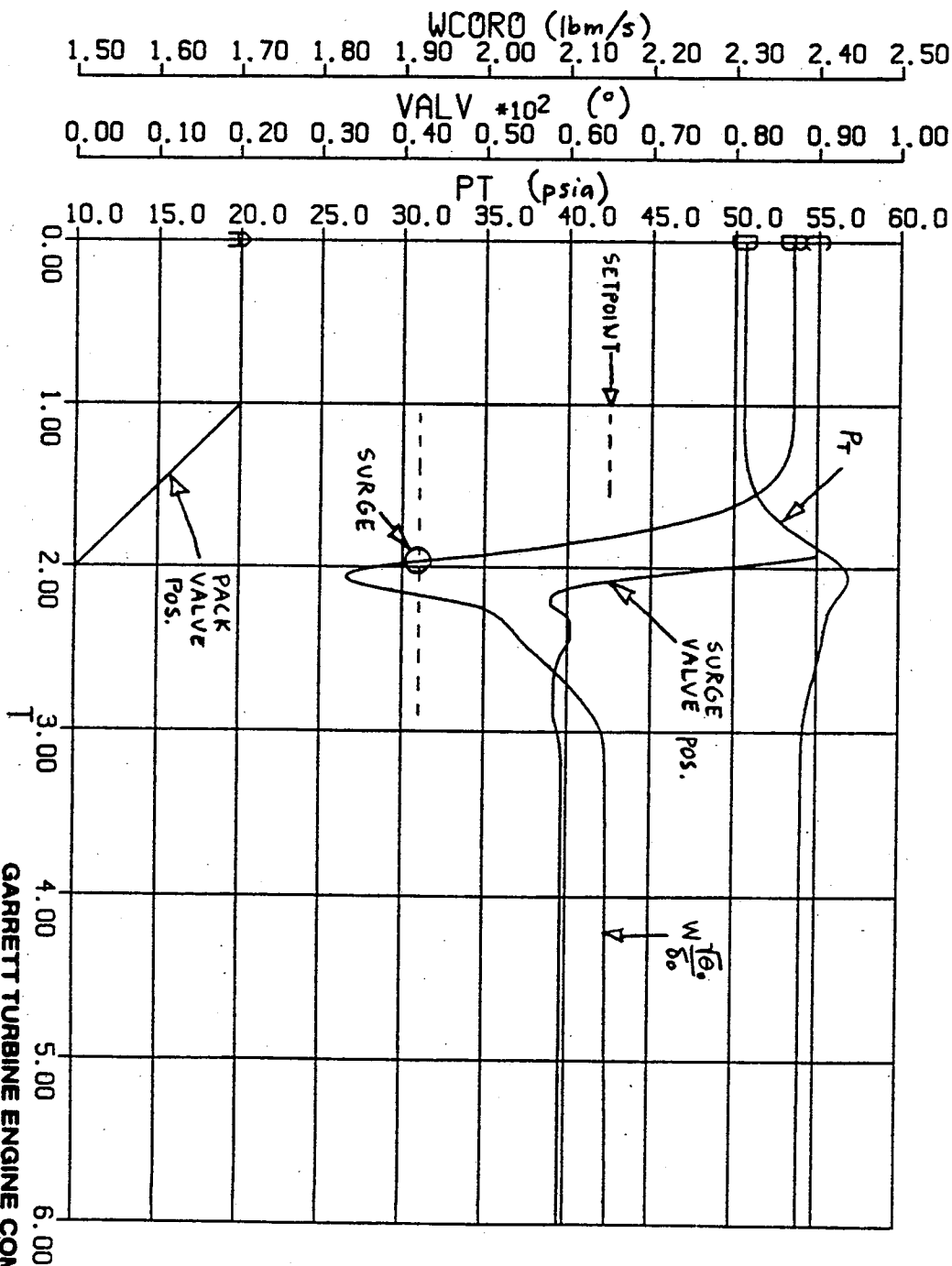
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VALVE ACTUATION TYPES

B. PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM (B1-B)

1 SEC PACK VALVE CLOSURE



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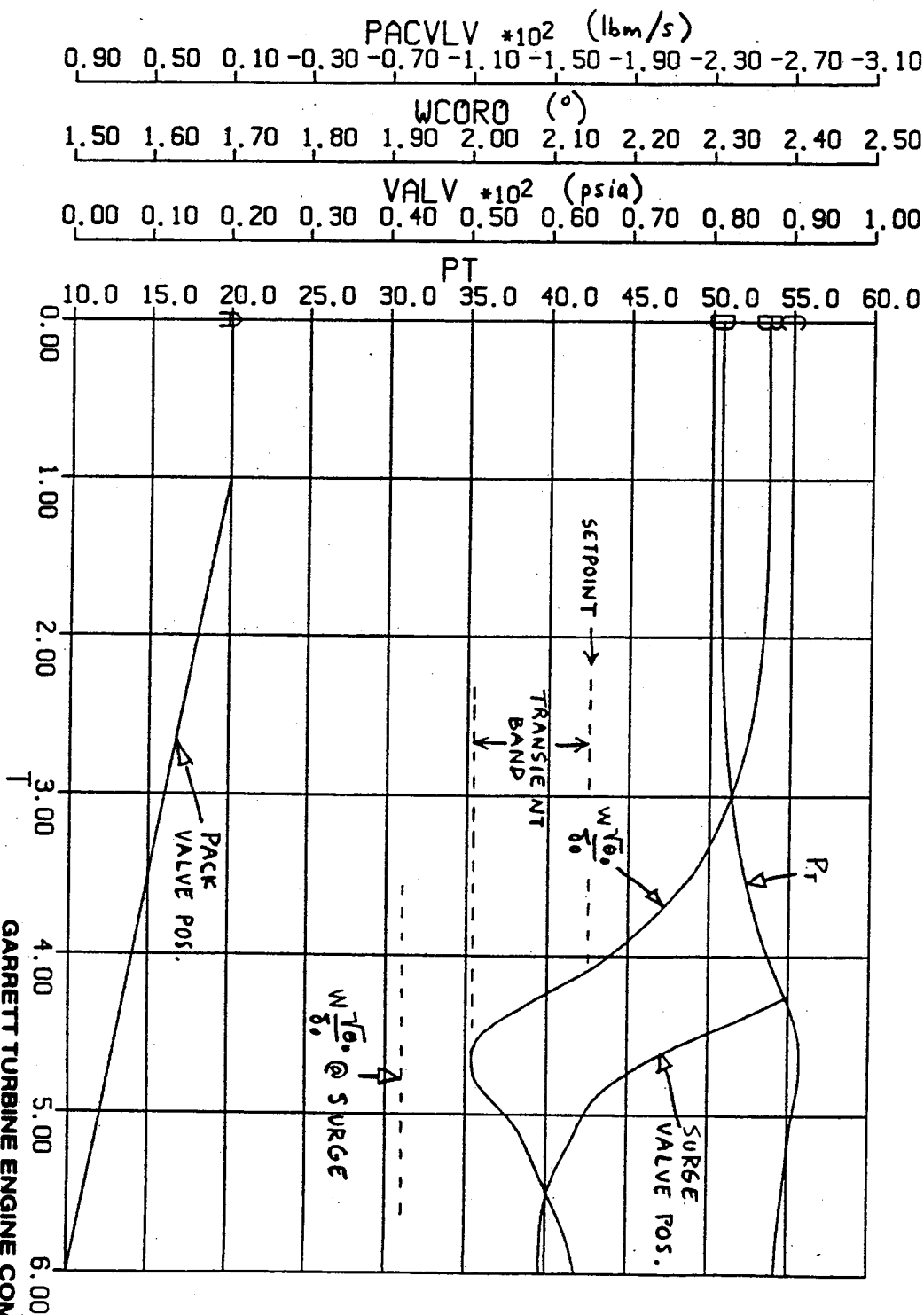
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VALVE ACTUATION TYPES

B. PNEUMATIC POWER/PNEUMATIC SIGNAL/ELECTRONIC TRIM (B1-B)

5 SEC PACK VALVE CLOSURE



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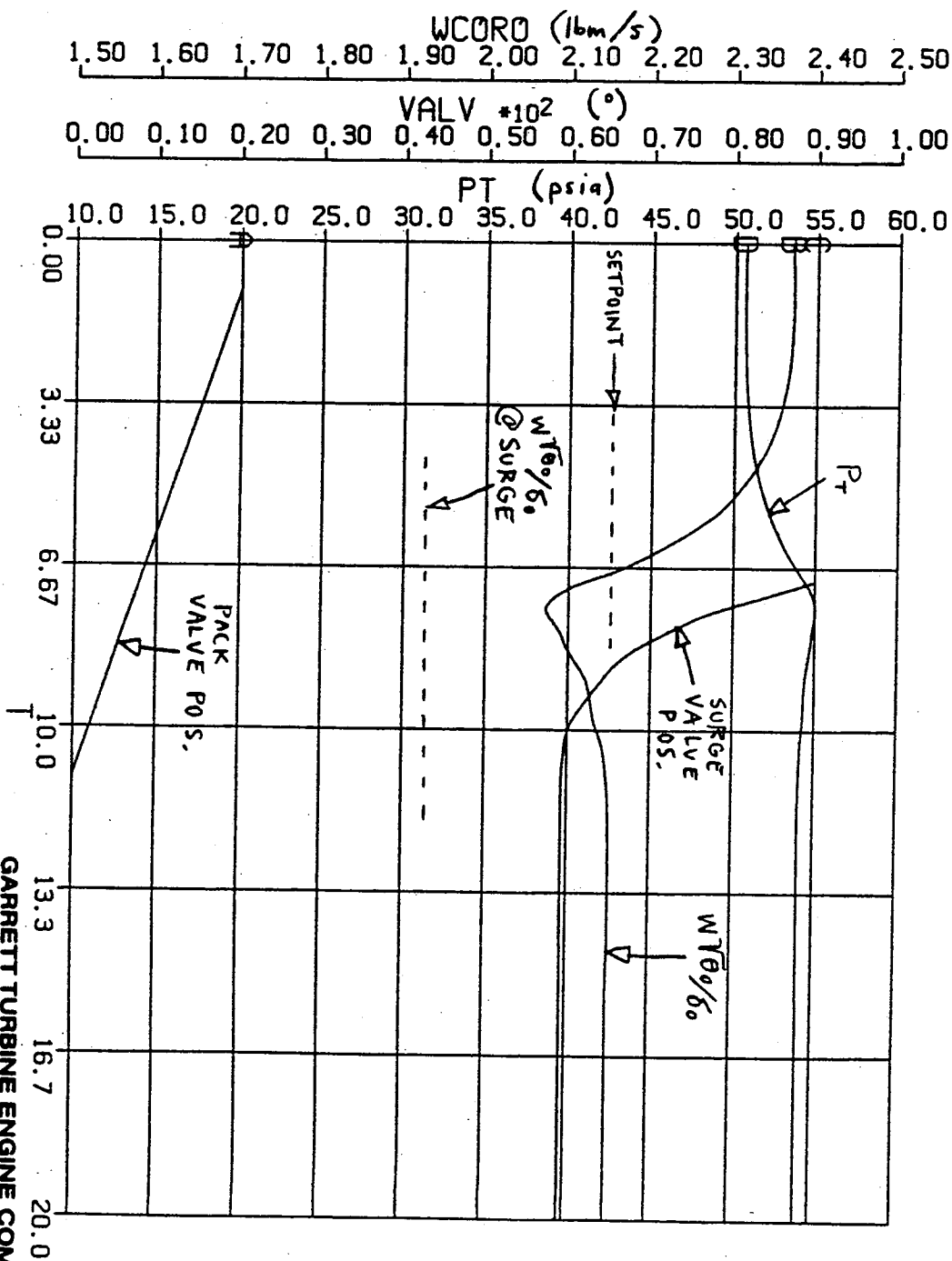
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VALVE ACTUATION TYPES

B. PNEUMATIC POWER/PNEUMATIC SIGNAL/ELECTRONIC TRIM (B1-B)

10 SEC PACK VALVE CLOSURE



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VALVE ACTUATION TYPES

B. PNEUMATIC POWER / PNEUMATIC SIGNAL / ELECTRONIC TRIM

- B1-B or MD-11 -TYPE VALVE IS A PROVEN DESIGN
- DIRECT ΔP INPUT FROM THE FLOW SENSOR IS THE PRIMARY SIGNAL. VALVE ANGLE IS A FUNCTION OF ΔP , WITH ELECTRONIC SETPOINT TRIM PROVIDING ACCURACY. HAS NO QUICK-DUMP FEATURE.
- FREQUENCY RESPONSE (TO ΔP) IS MUCH FASTER THAN THE 331-200/250 VALVE: ACTS LIKE A SECOND-ORDER TERM AT 25 RAD/SEC COMPARED TO ≈ 6 RAD/SEC FOR 331-200 VALVE
- HOWEVER, FREQUENCY RESPONSE IS STILL TOO SLOW TO HANDLE A FAST (1 SEC) PACK VALVE CLOSURE. AIRCRAFT VALVES WOULD HAVE TO BE SLOWED DOWN AND/OR CLOSURE SIGNALS PROVIDED TO ELECTRONIC CONTROLLER.
- BASICALLY LINEAR SYSTEM IS UNDERSTOOD WITH CLASSICAL CONTROL ANALYSIS METHODS. INSTABILITY IS NOT LIKELY.
- DUCT PRESSURE DOES NOT DROP SIGNIFICANTLY DURING TRANSIENTS
- DIRECT ΔP INPUT TO VALVE CAN PROVIDE BACKUP OPERATION (WITH REDUCED PERFORMANCE) IF TRANSDUCER FAILS.

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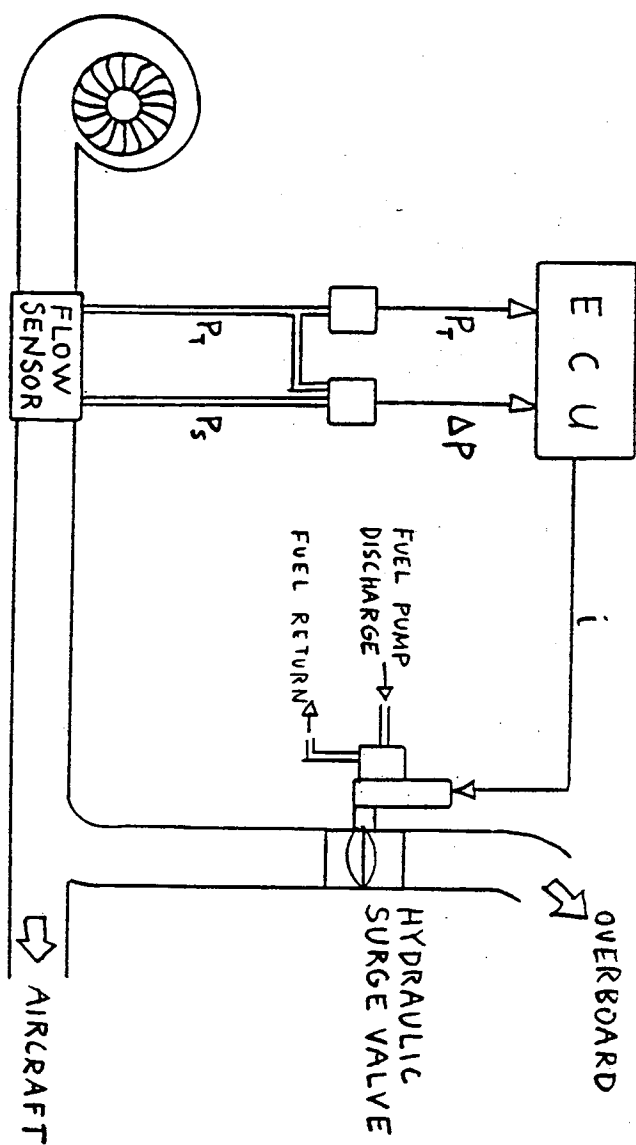
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VALVE ACTUATION TYPES

C. HYDRAULIC POWER / ELECTRONIC SIGNAL

SCHEMATIC



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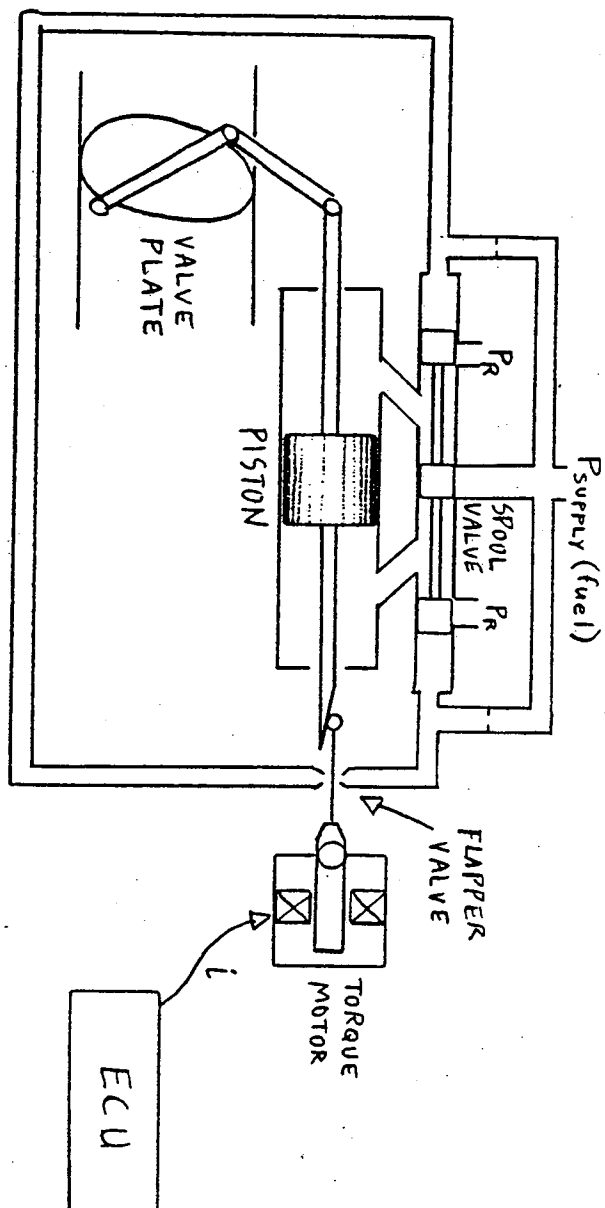
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VALVE ACTUATION TYPES

C. HYDRAULIC POWER / ELECTRONIC SIGNAL

POSSIBLE HYDRAULIC SURGE VALVE SCHEMATIC



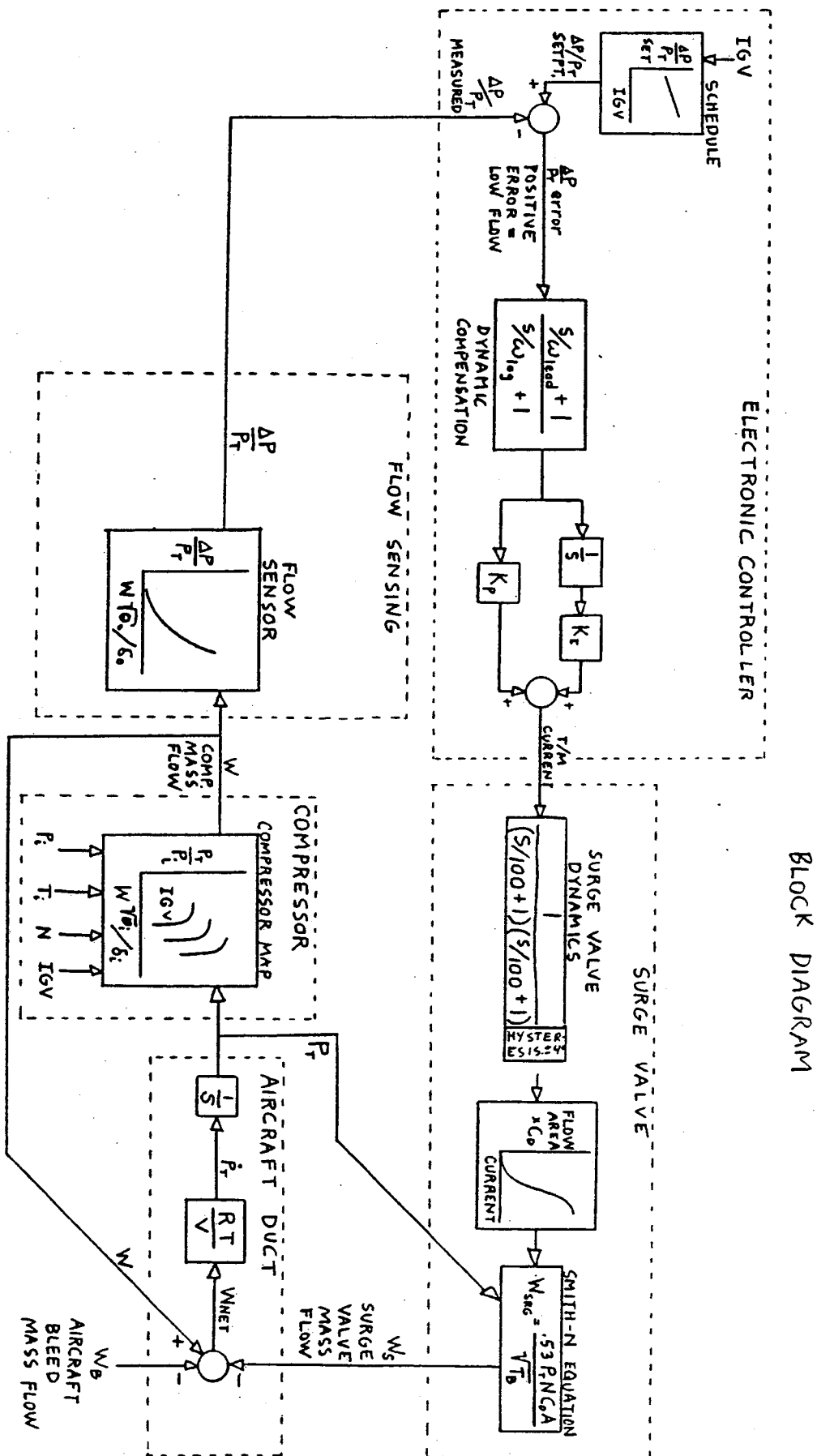
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VALVE ACTUATION TYPES



C. HYDRAULIC POWER / ELECTRONIC SIGNAL



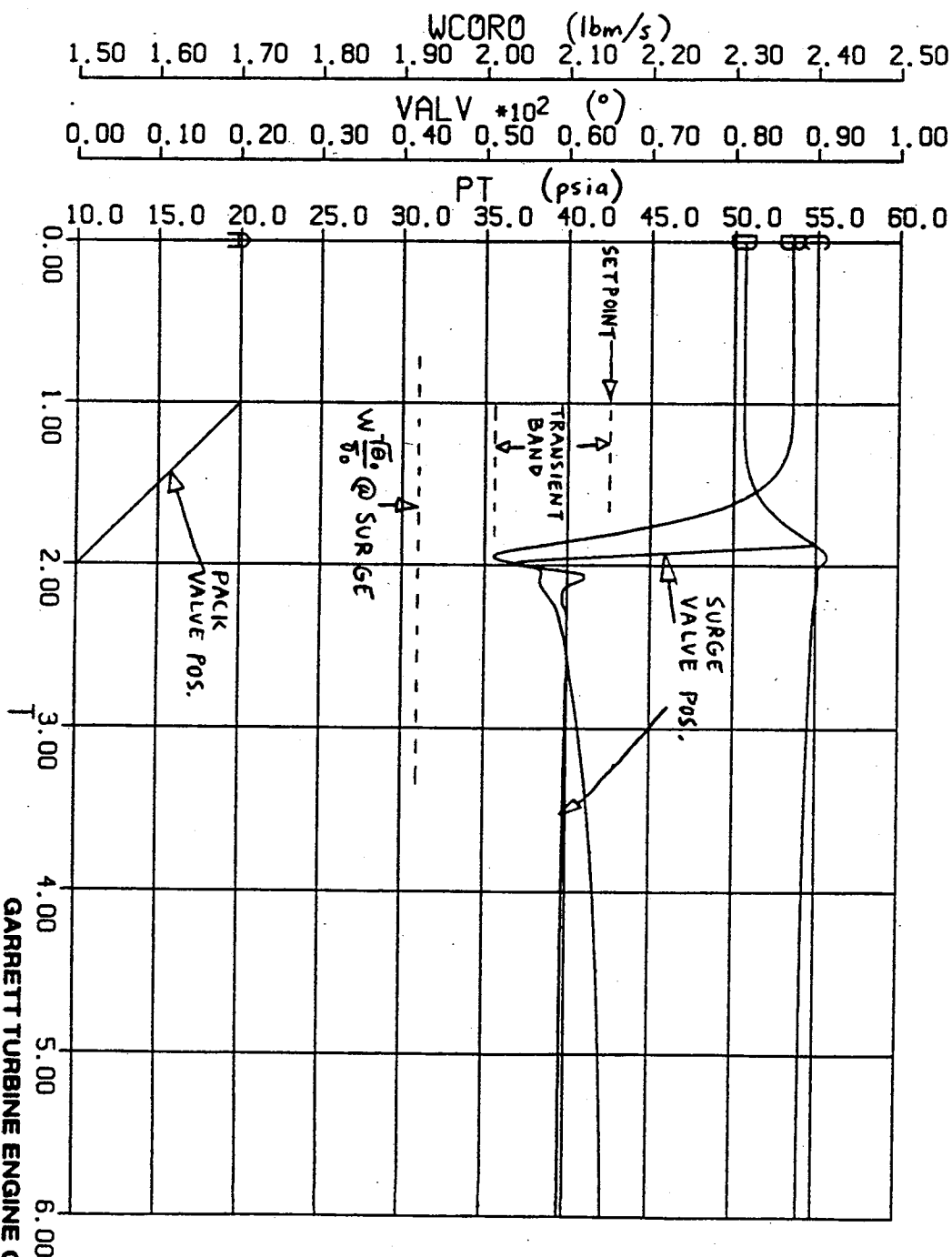
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C. HYDRAULIC POWER/ELECTRONIC SIGNAL

VALVE ACTUATION TYPES

1 SEC PACK VALVE CLOSURE



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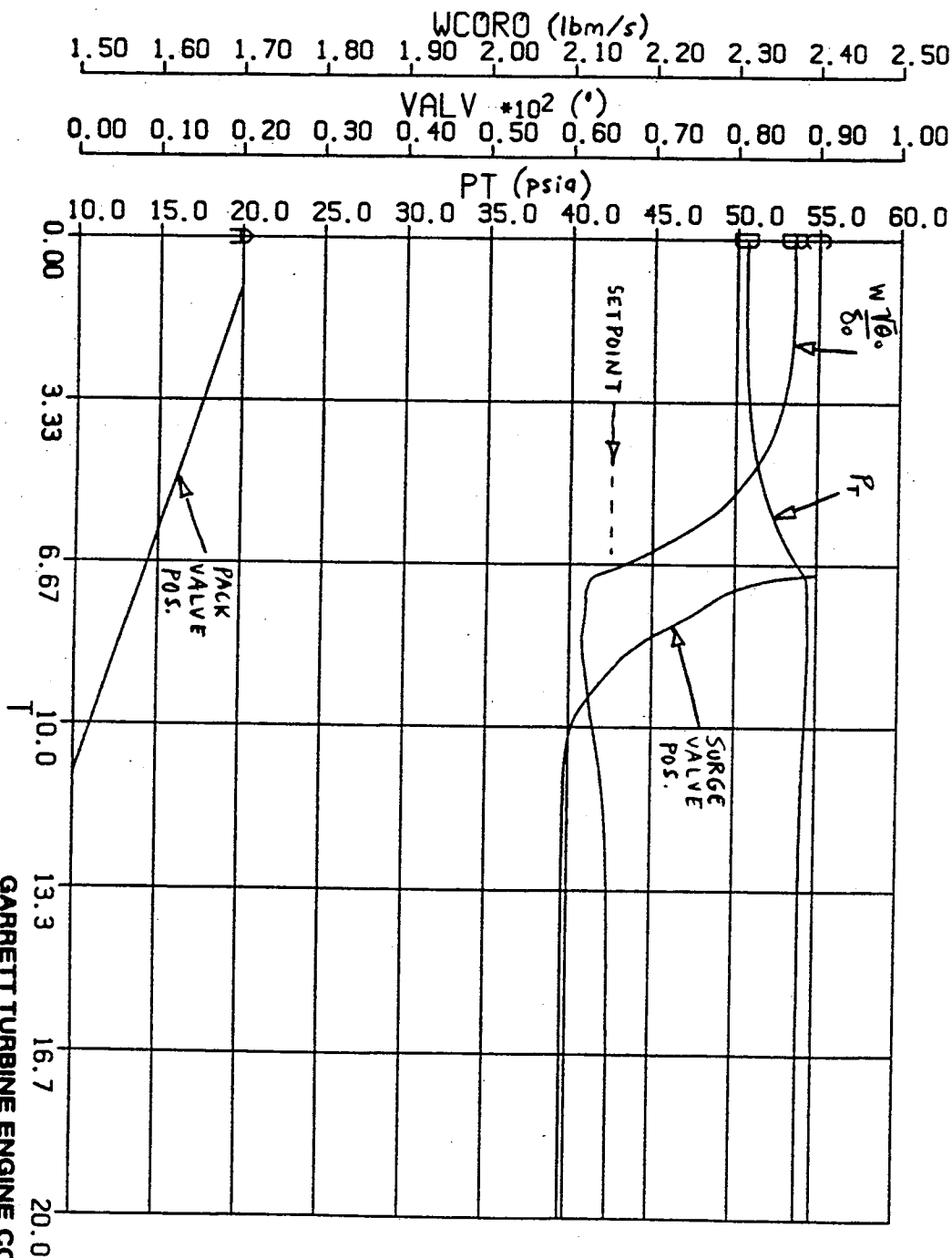
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C. HYDRAULIC POWER/ELECTRONIC SIGNAL

VALVE ACTUATION TYPES

10 SEC PACK VALVE CLOSURE



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VALVE ACTUATION TYPES

C. HYDRAULIC POWER / ELECTRONIC SIGNAL

- HYDRAULIC SURGE VALVE WOULD BE POWERED BY HIGH PRESSURE FUEL, CONTROLLED BY TORQUE MOTOR INPUT FROM ELECTRONICS
- A NEW IDEA, BUT EXPERIENCE WITH FUEL-POWERED HYDRAULIC IGV ACTUATOR ON 331-200/250 HAS BEEN GOOD.
- THE ASSUMED FREQUENCY RESPONSE (2nd ORDER TERM AT 100 rad/sec) IS VERY FAST; PRELIMINARY STUDIES BY VENDORS SUPPORT FEASIBILITY.
- CAN HANDLE A PACK VALVE 2 SEC. CLOSURE WITH ABOUT THE SAME TRANSIENT BAND AS THE 331-200/250 USES. (STILL NOT AS GOOD AS 331-200/250 TRANSIENT CAPABILITY)
- SURGE CONTROL SYSTEM IS A BASICALLY LINEAR DYNAMIC SYSTEM; CLASSICAL CONTROL TECHNIQUES CAN BE USED TO INSURE SYSTEM STABILITY.
- DUCT PRESSURE WILL NOT DROP SIGNIFICANTLY DURING TRANSIENTS
- TRANSIENT CAPABILITY CAN EXTEND TO VERY FAST AIRCRAFT VALVES IF OPEN-LOOP ELECTRONIC SIGNALS ARE AVAILABLE

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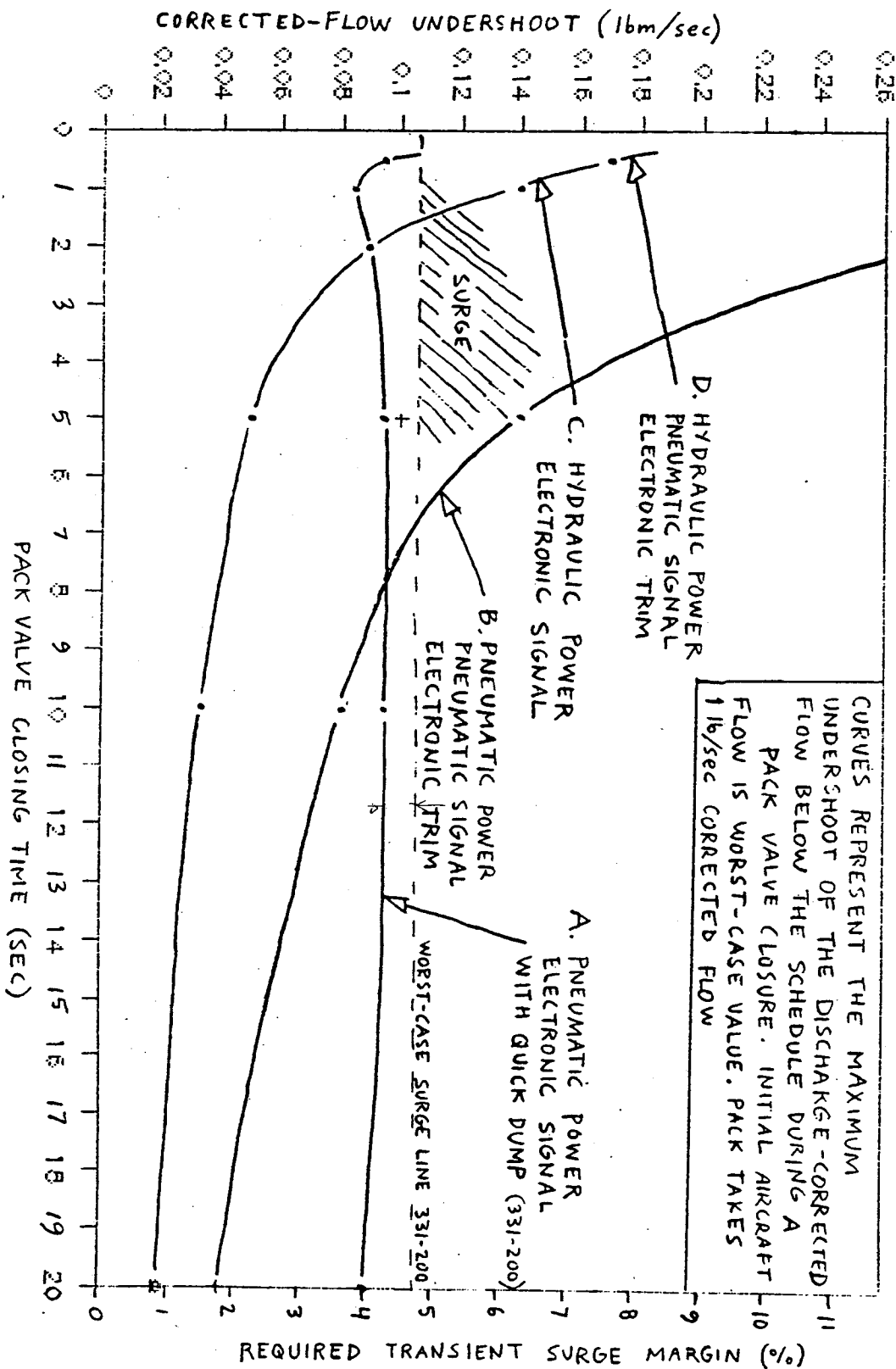
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VALVE ACTUATION TYPES

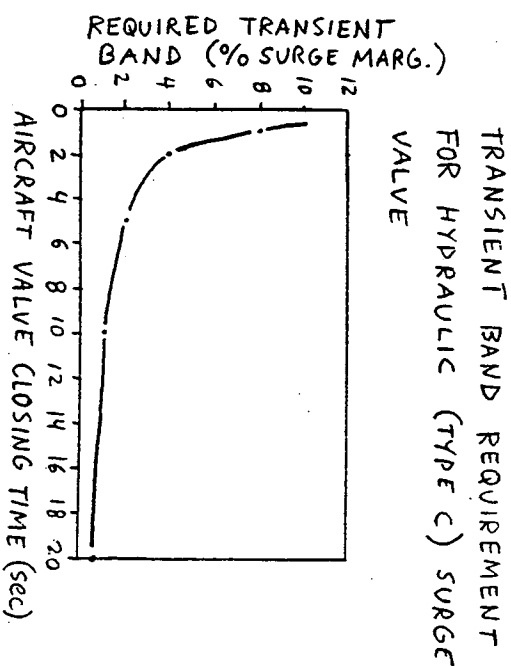
COMPARISON OF TRANSIENT BANDS





AIRCRAFT FLOW TRANSIENTS STRONGLY AFFECT SURGE CONTROL SYSTEM

- THE REQUIRED TRANSIENT BAND IS A VERY STRONG FUNCTION OF AIRCRAFT VALVE CLOSING TIME, OR RATE OF CHANGE OF AIRCRAFT FLOW.
- A PRACTICAL LIMIT FOR TRANSIENT BAND SIZE IS ABOUT 5% SURGE MARGIN. A TYPE B (MD-11) PNEUMATIC SURGE VALVE COULD OPERATE IN THAT BAND IF ALL FLOW TRANSIENTS WERE SLOWER THAN 0.6 LB/SEC/SEC, OR ABOUT 6 SECOND PACK VALVE CLOSING. FASTER FLOW TRANSIENTS WOULD HAVE TO BE ELECTRONICALLY SIGNED TO THE ECU.
- A SIMILAR CONSTRAINT FOR A TYPE C (HYDRAULIC) SURGE VALVE WOULD BE 2 LB/SEC/SEC, OR ABOUT 2 SECOND PACK VALVE CLOSING TIME. FASTER VALVES COULD BE HANDLED WITH ELECTRONIC SIGNALS FROM THE AIRCRAFT.



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TRANSIENT BAND CAN DEPEND ON OPERATING MODE

- PERHAPS THE TRANSIENT BAND CAN BE SMALLER IN MES MODE.
- QUESTION FOR BOEING : SINCE THE AIR TURBINE STARTER NOZZLE IS A FIXED AREA, CAN WE ASSUME THAT THE AIRCRAFT FLOW IS QUITE STEADY IN MES MODE, REDUCING THE TRANSIENT BAND TO NEARLY ZERO ? (WILL ANY VALVES BE OPENING AND CLOSING DURING MES MODE ?)

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FLOW MEASUREMENT TYPES

SEVERAL TYPES OF FLOW MEASUREMENT ARE POSSIBLE

A

 ΔP and P_t PRESSURE SIGNALS WITH TRANSDUCERS

- 1 STATIC RING WITH BUMP & TOTAL PITOT TUBE (331-200/250)
- 2 ADJUSTABLE STATIC PROBE WITH BUMP & TOTAL PROBE
- 3 VENTURI STATIC & ADJUSTABLE TOTAL PROBE
- 4 DIFFUSER STATIC & ADJUSTABLE TOTAL PROBE

B

HOT-WIRE PROBE

C

VORTEX-SHEDDING FLOW SENSOR

REMINDER: STEADY-STATE TOLERANCE BAND IS DETERMINED
MOSTLY BY THE TYPE OF FLOW MEASUREMENT

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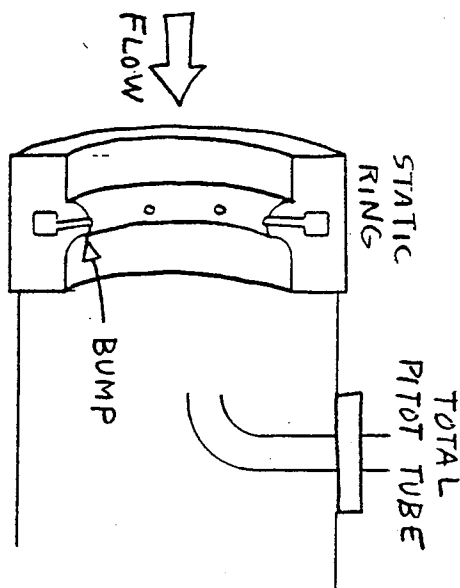
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FLOW MEASUREMENT TYPES

STATIC RING & PITOT TUBE ARE USED ON 331-200

- STATIC RING'S BUMP PROVIDES TWICE THE DP SIGNAL LEVEL OF A WALL STATIC WITH VERY LITTLE FLOW RESTRICTION
- RING AVERAGES STATICS AROUND THE DUCT
- RING IS DIFFICULT TO MAKE & HEAVY. PARTS ARE NOT FLOW TESTED; INCONSISTENT STATIC SIGNALS INCREASE THE TOLERANCE BAND.



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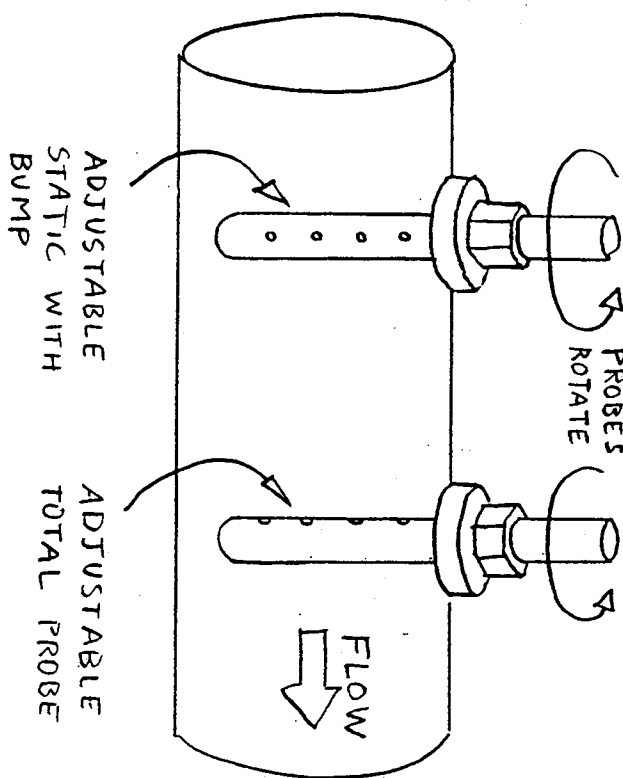
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ADJUSTABLE PROBES ARE SIMPLE

FLOW MEASUREMENT TYPES

- ADJUSTABLE PROBE CAN BE EITHER STATIC OR TOTAL
- USED AS A STATIC, THE TUBE ACTS AS A BUMP, DOUBLING THE DP SIGNAL WITH LITTLE FLOW RESTRICTION
- ADJUSTABILITY ALLOWS FLOW TESTING AND PRECISE CALIBRATION, REDUCING THE TOLERANCE BAND (POSSIBLY CUTTING IT IN HALF)



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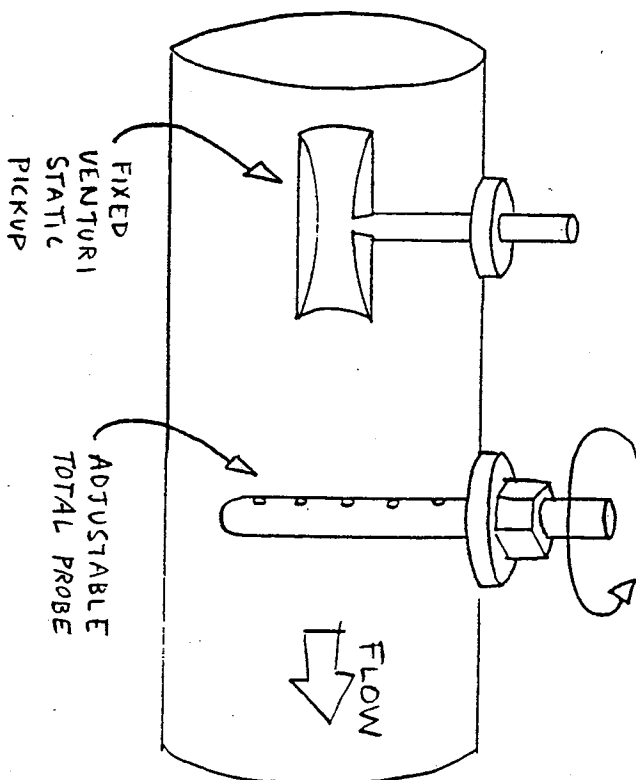
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FLOW MEASUREMENT TYPES

ADJUSTABLE TOTAL PROBE CAN BE USED WITH VENTURI STATIC


- VENTURI STATIC PROVIDES ABOUT 3 TIMES THE ΔP LEVEL OF A BUMP, BUT AT THE EXPENSE OF SOME FLOW RESTRICTION
- HIGHER ΔP LEVEL ALLOWS USE OF A MORE RUGGED TRANSDUCER
- ADJUSTABLE TOTAL PROBE ALLOWS PRECISE CALIBRATION BY FLOW TESTING, REDUCING THE TOLERANCE BAND



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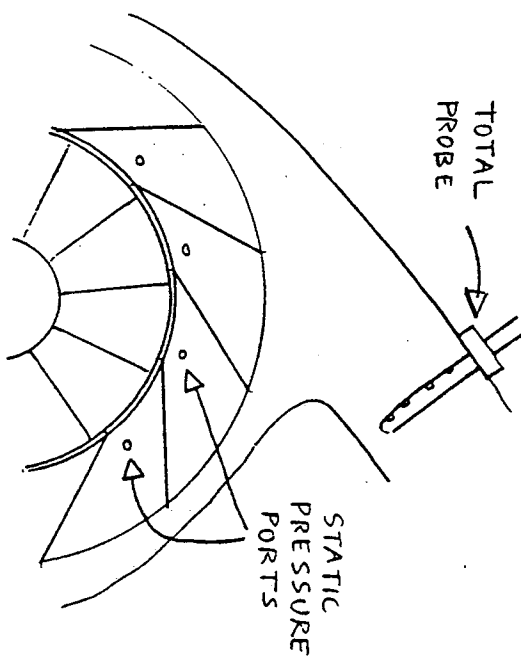
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|  | FLOW MEASUREMENT TYPES |
|---|--|
| | DIFFUSER STATICS GIVE LARGE SIGNAL, LOW LOSSES |

- STATIC PRESSURE PORTS IN THE DIFFUSER WITH TOTAL PRESSURE PROBE IN THE DUCT ALLOWS LARGE ΔP SIGNAL (3 TIMES THAT OF A BUMP?) WITH VERY LITTLE FLOW RESTRICTION
- TOTAL PROBE CAN PROVIDE ADJUSTABILITY

- A SIMILAR TYPE OF SENSING WHICH USES $\Delta P/\Delta P$ (ONLY DIFFUSER STATICS) IS IN THE 331-350 PROPOSAL AND ON THE GTCI31 ENGINE. FURTHER TESTING HAS SHOWN THAT THE SURGE LINE IN TERMS OF $\Delta P/\Delta P$ IS NOT INDEPENDENT OF IGV POSITION, AS ORIGINALLY THOUGHT,



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FLOW MEASUREMENT TYPES

THREE METHODS OF SENSOR ADJUSTMENT ARE POSSIBLE

1. BENCH-TEST EACH DUCT SECTION TO CALIBRATE THE FLOW SENSOR,
THIS METHOD ALLOWS THE DUCT SECTION TO BE REPLACEABLE
ON THE FLIGHT LINE, WHILE IMPROVING THE ACCURACY.
NOT APPLICABLE WITH DIFFUSER STATICS.
2. CALIBRATE THE FLOW SENSOR AFTER ENGINE ASSEMBLY.
THIS ELIMINATES THE EFFECTS OF DIFFERING FLOW FIELDS
AMONG COMPRESSORS. FLOW SENSOR WOULD NOT BE AN L.R.U.
MAYBE A SIMPLE PROCEDURE FOR USE BY AIRLINES COULD BE DEvised.
3. CALIBRATE THE FLOW SENSOR AFTER ENGINE ASSEMBLY AND AFTER
SURGING THE LOAD COMPRESSOR TO FIND ITS SURGE LINE.
THIS METHOD GIVES THE SMALLEST POSSIBLE STEADY-STATE
TOLERANCE BAND BY CALIBRATING OUT THE DIFFERENCES
AMONG FLOW SENSORS, COMPRESSOR FLOW FIELDS, COMPRESSOR
SURGE LINES, AND EVEN LAB MEASURING EQUIPMENT.
FLOW SENSOR WOULD NOT BE AN L.R.U. (BUT TRANSDUCERS
WOULD BE L.R.U.s)

NOTE PRESSURE PROBES ARE NON-FLOWING DEVICES
AND ARE VERT KILLABLE, THEY WOULD NOT
NEED TO BE KILLED

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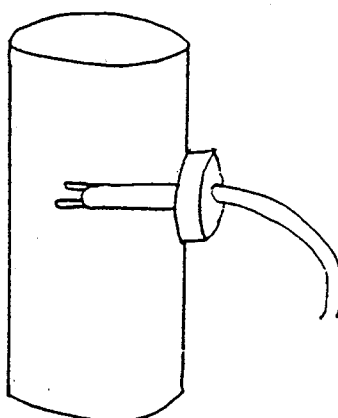
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FLOW MEASUREMENT TYPES

HOT-WIRE FLOW SENSORS MEASURE MASS FLOW

- GTEC HAS TESTED HOT-RESISTOR FLOW SENSORS IN A COMPANY-SPONSORED PROGRAM.
- SINCE HOT-RESISTOR FLOW SENSORS MEASURE MASS FLOW, THEIR SIGNAL MUST BE ACCOMPANIED BY A PRESSURE AND A TEMPERATURE MEASUREMENT TO OBTAIN DISCHARGE-CORRECTED FLOW. THE TOLERANCES OF THESE EXTRA MEASUREMENTS REDUCE THE OVERALL ACCURACY.
- RUGGED SENSORS HAVE A RESPONSE SPEED WHICH IS TOO SLOW FOR SURGE CONTROL.



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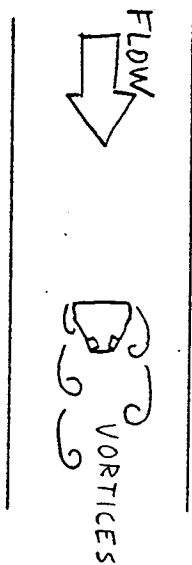
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FLOW MEASUREMENT TYPES

VORTEX-SHEDDING FLOW SENSORS MEASURE VOLUME FLOW

- GTEC HAS TESTED VORTEX-SHEDDING FLOW SENSORS IN A COMPANY-SPONSORED PROGRAM. THE TESTED SENSORS WERE HEAVY, INDUSTRIAL METERS NOT SUITABLE FOR AIRCRAFT USE.
- FREQUENCY OF VORTICES IS PROPORTIONAL TO VOLUME FLOW, INDEPENDENT OF PRESSURE OR TEMPERATURE. TO OBTAIN DISCHARGE-CORRECTED FLOW, SIGNAL WOULD BE ACCOMPANIED BY A THERMOCOUPLE.
- RESPONSE SPEED CAN BE VERY FAST.
- A SMALL VORTEX-SHEDDING SENSOR USED ON AUTOMOBILES IS CURRENTLY BEING INVESTIGATED. PRESSURE DROP OF THE SENSOR MAY BE A CONCERN.



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COMPARISON STUDY SUMMARY

331-200 FLOW
SENSOR
ADJUSTABLE
FLOW SENSOR

| | STEADY-STATE TOLERANCE * | TRANSIENT BAND FOR 1 SEC PACK VALVE | REQUIRED SURGE MARGIN AT SPEC. POINT * | REQUIRED PRESSURE MARGIN AT SET POINT ** |
|---|--|--|---|--|
| A PNEUMATIC POWER/ ELECTRONIC SIGNAL (331-200/250 SYSTEM) | $\pm 5.2\% \text{ SM}^{\dagger}$ $\pm 3.9\% \text{ SM}$ | $4.3\% \text{ SM}$ $4.3\% \text{ SM}$ | $14.7\% \text{ SM}$ $12.1\% \text{ SM}$ | 2.5% 2.5% |
| B PNEUMATIC SIGNAL/ PNEUMATIC POWER/ ELECTRONIC TRIM | $\pm 5.2\% \text{ SM}$ $\pm 3.9\% \text{ SM}$ | $19.6\% \text{ SM}$ (5.3% FOR 5 SEC VALV) $19.6\% \text{ SM}$ | $30.0\% \text{ SM}$ (15.3% FOR 5 SEC VALV) $27.4\% \text{ SM}$ (12.7% FOR 5 SEC VALV) | 4.0% 4.0% |
| C HYDRAULIC POWER/ ELECTRONIC SIGNAL | $\pm 5.2\% \text{ SM}$ $\pm 3.9\% \text{ SM}$ | $8.0\% \text{ SM}$ $8.0\% \text{ SM}$ | $18.4\% \text{ SM}$ $15.8\% \text{ SM}$ | 4.0% 4.0% |
| D HYDRAULIC POWER/ PNEUMATIC SIGNAL/ ELECTRONIC TRIM | $\pm 5.2\% \text{ SM}$ $\pm 3.9\% \text{ SM}$ | $8.0\% \text{ SM}$ $8.0\% \text{ SM}$ | $18.4\% \text{ SM}$ $15.8\% \text{ SM}$ | 4.0% 4.0% |

NOTES: TRANS. BAND BASED ON: • CURRENT COMPRESSOR ESTIMATE • SL, STD DAY, 80°IGV • SETPT @ 12% SM • SURGE @ 1.92 lb/sec
• ASSUMED 767-400 DUCT VOLUME IS 60 000 in³

* ASSUMED $\pm .04 \text{ lb/sec}$ or $\pm 2\% \text{ SM}$ VARIATION AMONG COMPRESSOR SURGE LINES

\dagger SURGE MARGIN DEFINED AS $[(w\sqrt{P_0}/\delta_0)_{\text{OPERATING PT.}} - (w\sqrt{P_0}/\delta_0)_{\text{SURGE}}] / (w\sqrt{P_0}/\delta_0)_{\text{OPERATING PT.}}$

** PRESSURE RATIO (PR) MARGIN DEFINED AS $[(PR \text{ AT SURGE}) - (PR \text{ AT SETPOINT})] / (PR \text{ AT SETPOINT})$

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GTCP331-350 SURGE CONTROL SYSTEM SUMMARY

- TRANSIENT PERFORMANCE IS THE MOST DIFFICULT ASPECT OF LOAD COMPRESSOR SURGE CONTROL.
- THE AMOUNT OF SURGE MARGIN ALLOWED FOR STEADY-STATE TOLERANCE DEPENDS MOSTLY ON THE TYPE OF FLOW MEASUREMENT, WHILE THAT ALLOWED FOR TRANSIENTS DEPENDS MOSTLY ON THE TYPE OF SURGE VALVE ACTUATION.
- AIRCRAFT TRANSIENT FLOW REQUIREMENTS STRONGLY AFFECT THE CHOICE AND DESIGN OF THE SURGE CONTROL SYSTEM.
- ALL ASPECTS OF THE SURGE CONTROL SYSTEM AND ITS EFFECTS ON THE ENGINE ARE BEING CONSIDERED IN STUDYING THE ALTERNATIVES.

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GTCP331-350 SURGE CONTROL STUDY SUMMARY

- THE GTCP331-200/250 SURGE CONTROL SYSTEM DOES AN EXCELLENT JOB OF PROTECTING THE LOAD COMPRESSOR FROM SURGE WHILE USING A SMALL SURGE MARGIN. THIS IS MOSTLY DUE TO THE "KICKER" COMBINED WITH THE ORIFICES AND VOLUMES AND THE RESULTING EXTREMELY SMALL TRANSIENT FLOW UNDERSHOOT.
- HOWEVER, THESE SAME FEATURES CAUSE NUISANCE KICKS AND POSSIBLE INTERACTION WITH AIRCRAFT VALVES. WHEN THE SURGE VALVE KICKS, THE DUCT PRESSURE DROPS SIGNIFICANTLY. AT LEAST SOME "RELIABILITY" PROBLEMS ARE ROOTED IN THE KICKER AND LEAD-EFFECT ORIFICING.
- THERE IS NO FREE LUNCH. A NON-KICKING SURGE CONTROL SYSTEM CAN BE MORE INHERENTLY STABLE AND WOULD PREVENT DUCT PRESSURE DROPS, BUT IT IS DIFFICULT TO IMAGINE ONE WITH THE SAME TRANSIENT BAND AS THE 331-200/250 SYSTEM
- USE OF NON-KICKING SURGE VALVE WILL PROBABLY REQUIRE A VERY HIGH-FREQUENCY-RESPONSE ACTUATOR COMBINED WITH A SMALL RELAXATION OF AIRCRAFT VALVE TRANSIENT REQUIREMENTS OR THE USE OPEN-LOOP VALVE TRANSIENT SIGNALS TO THE APU.

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GTCP 331-350 SURGE CONTROL STUDY SUMMARY

- THE STEADY-STATE ACCURACY OF THE 331-200/250 SYSTEM CAN BE IMPROVED BY USE OF AN ADJUSTABLE FLOW SENSOR. CURRENT FAVORITE FLOW SENSOR TYPE IS DIFFUSER STATICS PLUS ADJUSTABLE TOTAL PROBE.
- CURRENT FAVORITE VALVE TYPE IS AN ELECTRO-HYDRAULIC FUEL-POWER SURGE VALVE.
- GTEC HAS THE EXPERTISE AND THE DESIRE TO MAKE AN EXCELLENT SURGE CONTROL SYSTEM FOR THE GTCP331-350 ON THE 767-400.

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